CAP Ascent Abort Aero Presentation for JAXA

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- Frank Green, Langley, LARC CAP manager
- Host of Ames, Dryden, Glenn, Johnson, Langley and Lockheed Martin CFD, WTT and database engineers and analysts

Briefing outline

- CAP and mode 1 ascent abort description
- Boost Phase Aero: AM JI
- Boost Phase Aero: 26-AA
- Lessons Learned, Issues, Recommendation and Summary

Background information

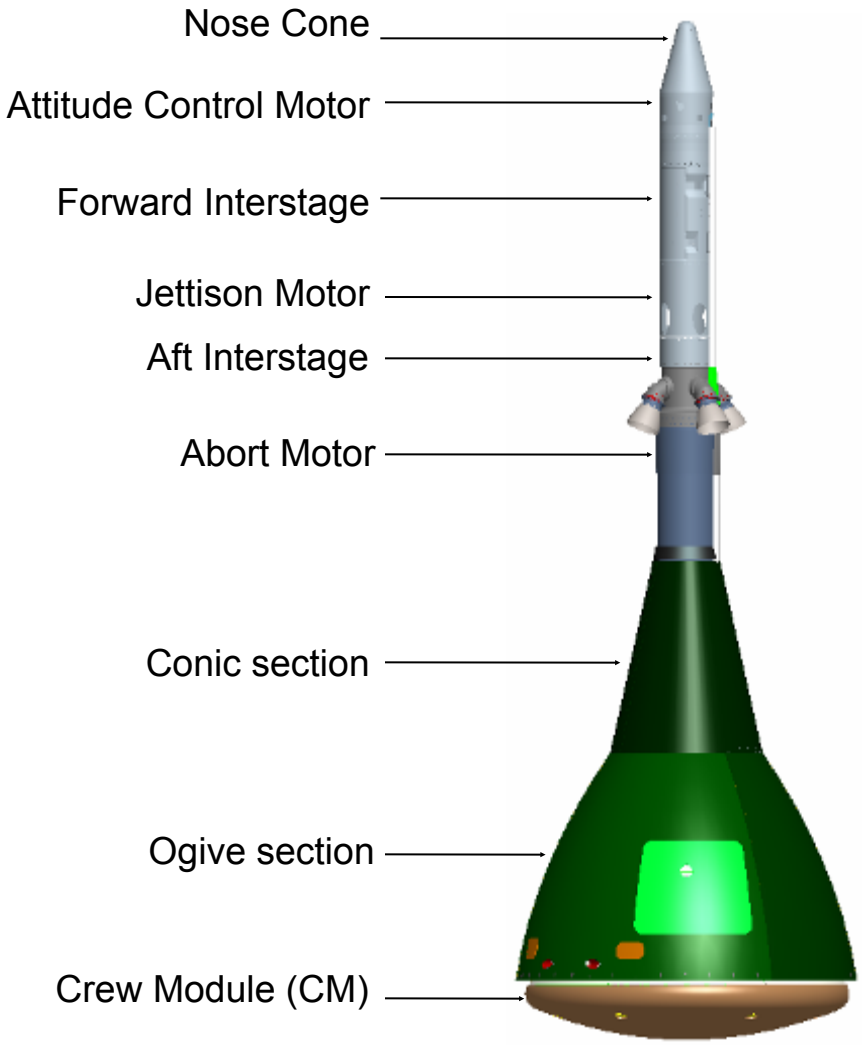
- **The CEV Aeroscience Project (CAP) is charged with delivering aerodynamic (and aerothermodynamic) environments to Orion for development of Orion vehicles**
  - Directed to use CFD to develop aerodynamic database to save costs
  - WTT program largely designed to validate CFD based database models and Apollo models
  - Aerodynamic configurations were going to be provided by the Prime Contractor upon selection
- **Suffice it to say, initial planning and direction did not survive long**
  - The configuration has been under an ongoing evolution since the beginning
  - Budgeting and resource allocations were way under for supporting and characterizing the configurations
  - Configuration has been very difficult to test and to analyze with CFD

Launch Abort Configuration

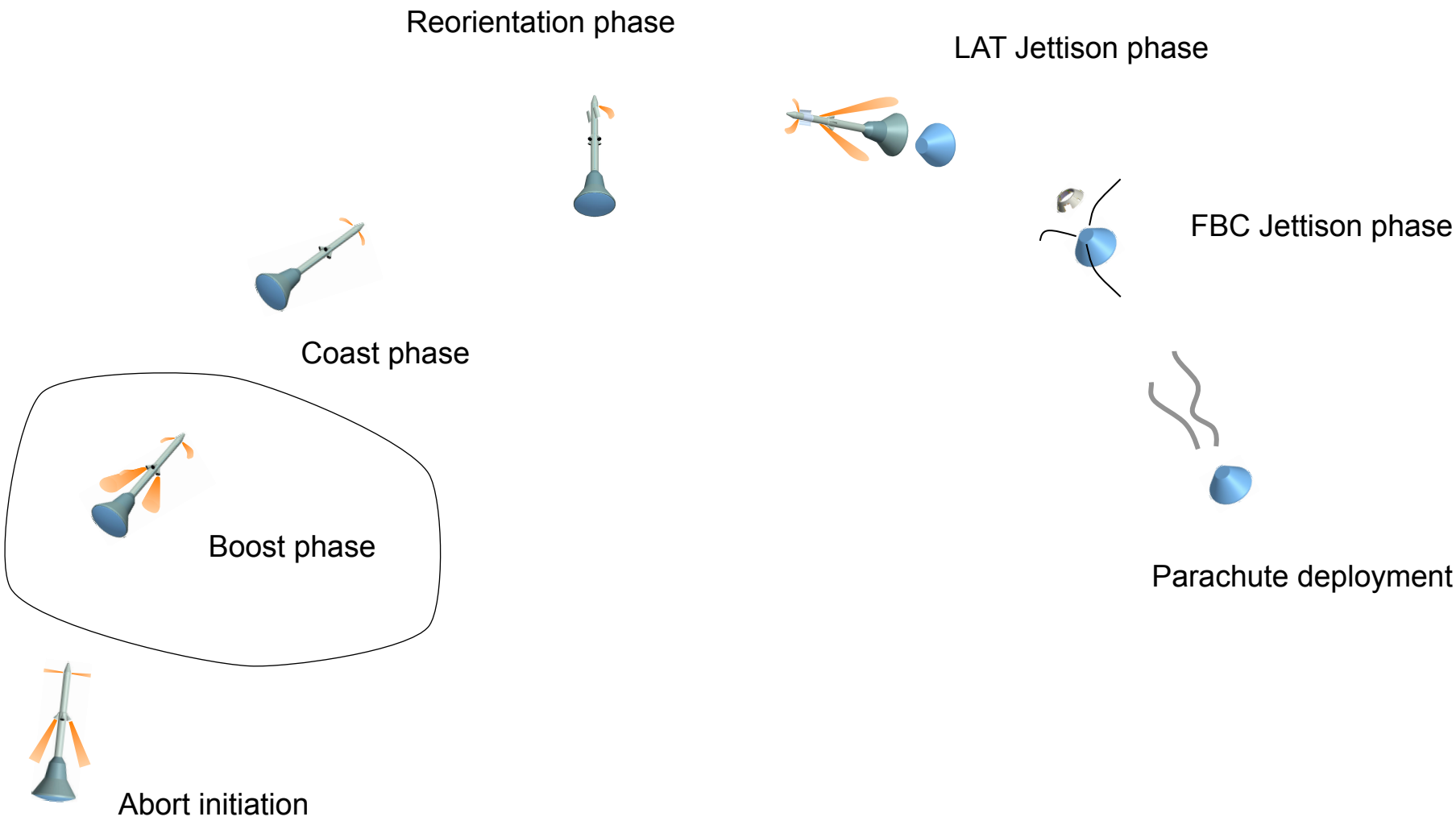
606D - mainline

605-068 - PA-1

Crew Module



Orion Mode 1 Ascent Abort Con-op



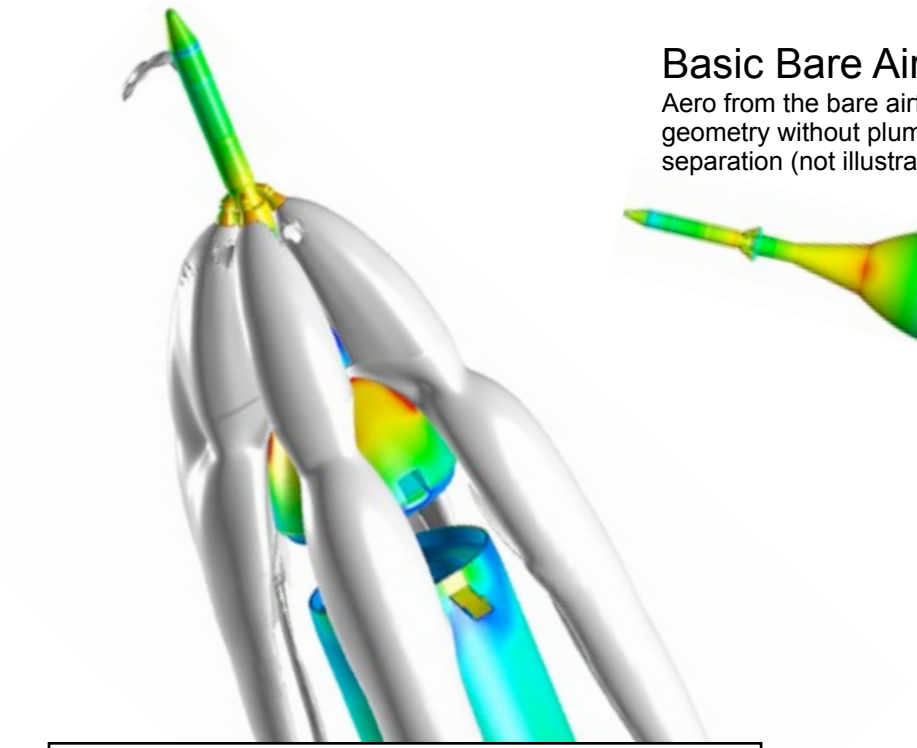
Aerodynamic Database Product

- **Currently at v0.62, possibly the most complex aerodynamic database product to have been produced**
  - CAP produces a drop-in aerodynamic database application programming interface (API) for GNC teams to drop into simulations
    - Typically, database tables and formulation are delivered and GNC codes the tables and formulation into simulation; CAP has taken over the “coding” part
    - A lot more time consuming then anticipated to ensure the API could be used on multiple platforms and multiple teams
  - 0° to 360° alpha/beta environments for 3 different configurations
  - Mach 0.3 to 6+ databases for 2 different configurations
  - 7 dimensional databases for LAT separation
  - 6 dimensional databases for Coast ACM JI
  - 5 dimensional + 4 dimensional databases for Boost AM JI + Boost ACM JI
  - Rate-based dynamic damping models for both LAV and CM
  - Uncertainties for 95% of aerodynamic terms

Big problems we've worked on

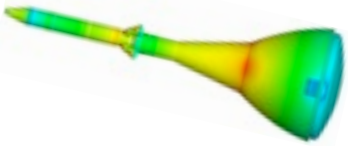
- **Boost phase transonic AM+ACM plume aero (plume and wake dominated flows)**
  - Vast 9 dimensional space with non-linear aero trends from Mach 0.9 to 2
  - 26-AA Abort Plumes and Separation wind tunnel test, obtained data on all plumes using cold air
- **Crew module + drogue chute dynamics (wake dominated flows)**
  - Langley TDT testing of CM configuration shows highly nonlinear dynamic damping characteristics
  - Langley VST testing of CM+drogue chute configuration shows combined system is more stable than simulations indicate (outside uncertainties)
    - Simulations use separately developed parachute and CM aero models
- **Crew module subsonic aerodynamics (wake dominated flows)**
  - Prediction of blunt body drag is difficult and we do not have a highly confident answer
  - 89-CA Langley NTF high Reynolds wind tunnel test shows that drag is sensitive to surface roughness even at flight Reynolds number

The vehicle flies like this



Basic Bare Airframe

Aero from the bare airframe geometry without plumes or separation (not illustrated)



The aero is discretized to make it possible to develop

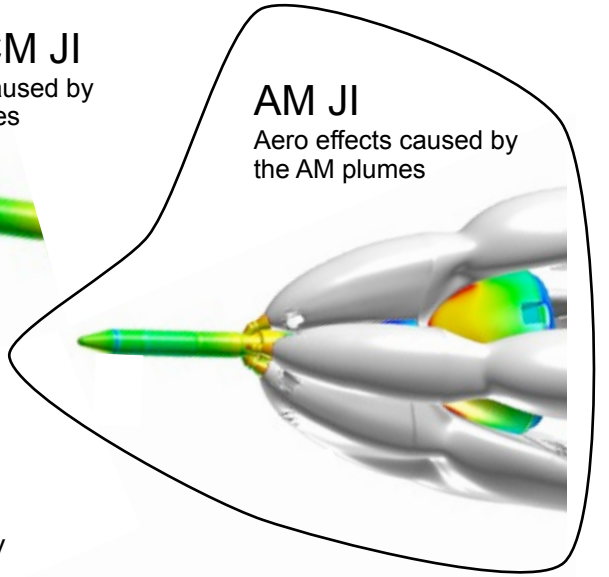
(As of today, CAP is not able to analyze or test with confidence the complete flight configuration with all plumes)

Boost ACM JI

Aero effects caused by the ACM plumes

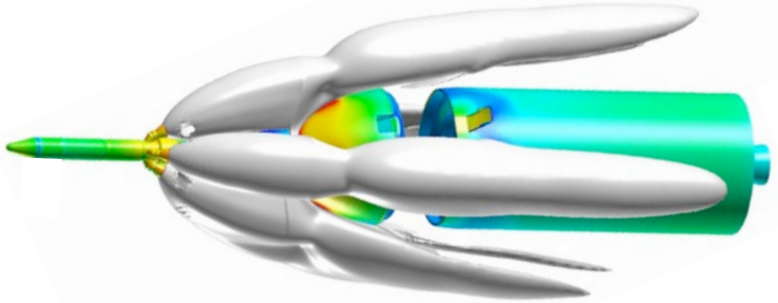
AM JI

Aero effects caused by the AM plumes



Separation

Aero effects caused by separation from the CLV



Total v0.60 LAV Boost Aerodynamics

= **Bare Airframe Static**

\+ Bare Airframe Dynamic

\+ **Abort Motor JI Increment**

\+ Boost ACM JI Increment

\+ Separation Increment

\+ **Bare Airframe Static Uncertainties**

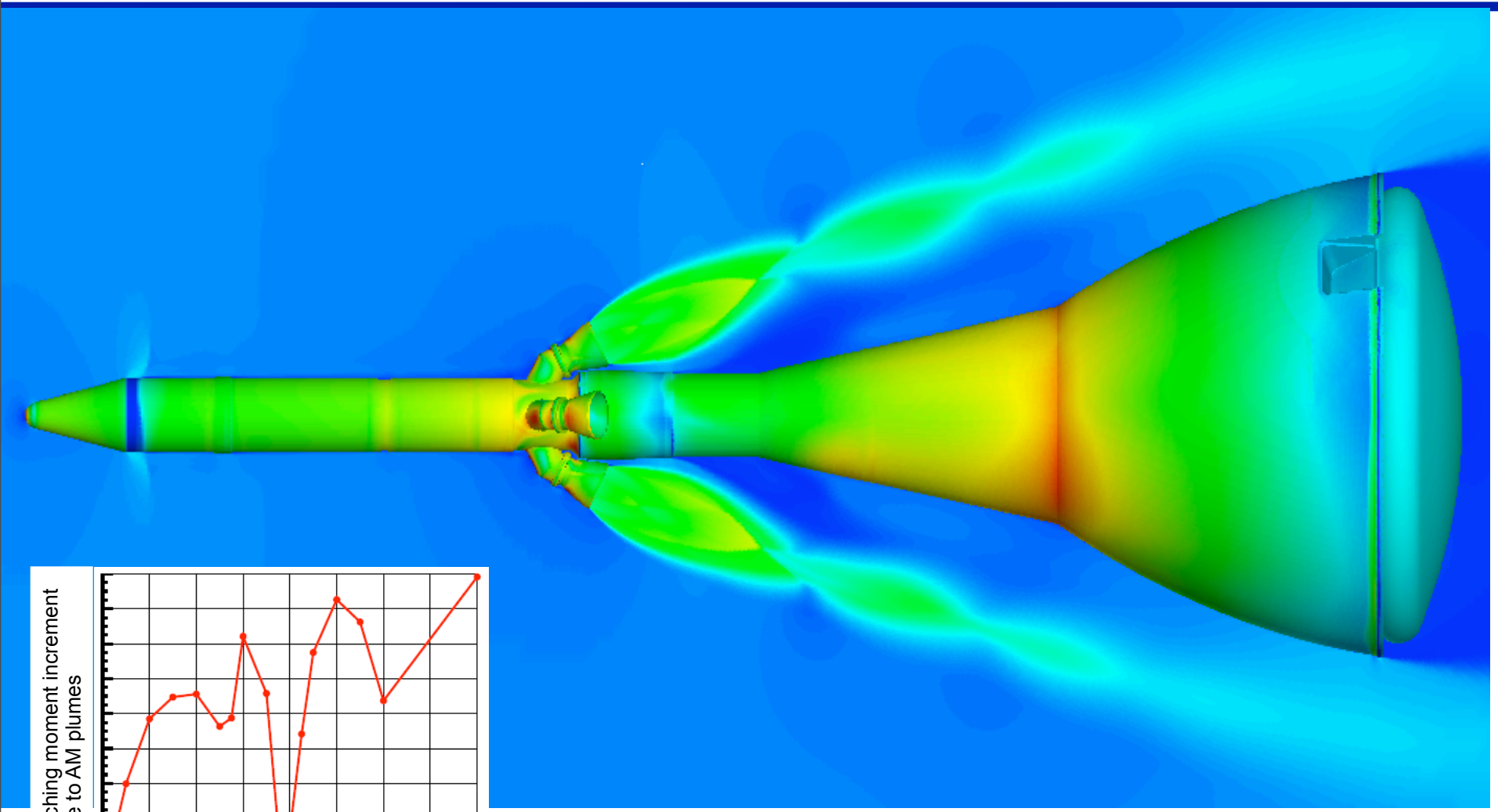
\+ Bare Airframe Dynamic Uncertainties

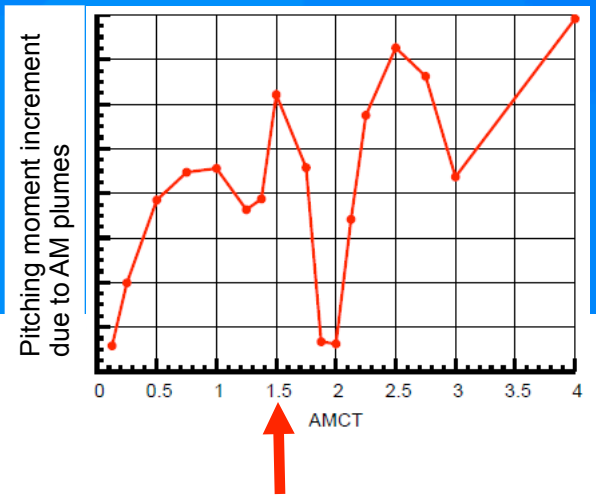
\+ **Abort Motor JI Inc Uncertainties**

\+ **Boost ACM JI Inc Uncertainties**

\+ Separation Inc Uncertainties

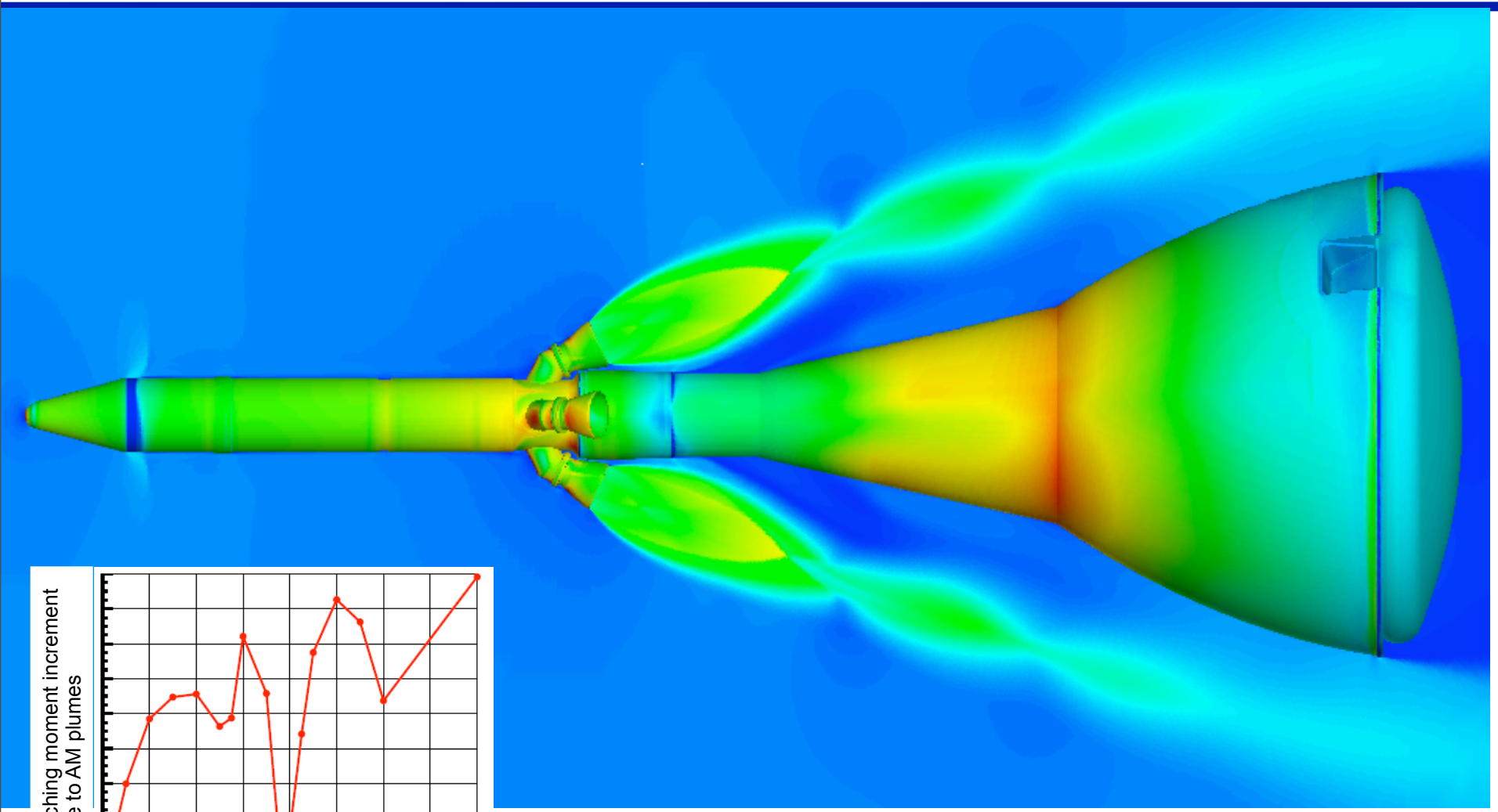
CT=1.5

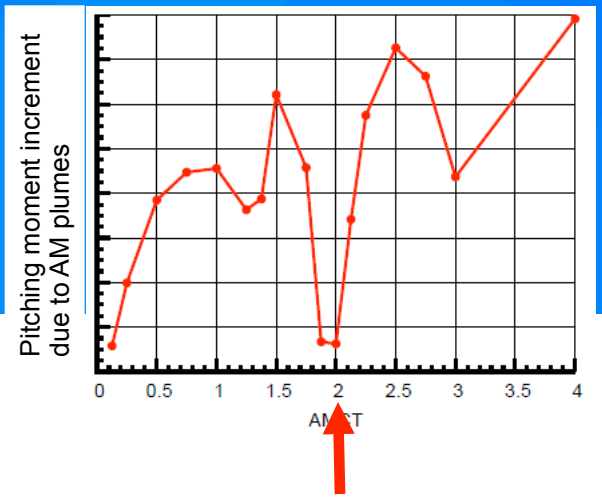




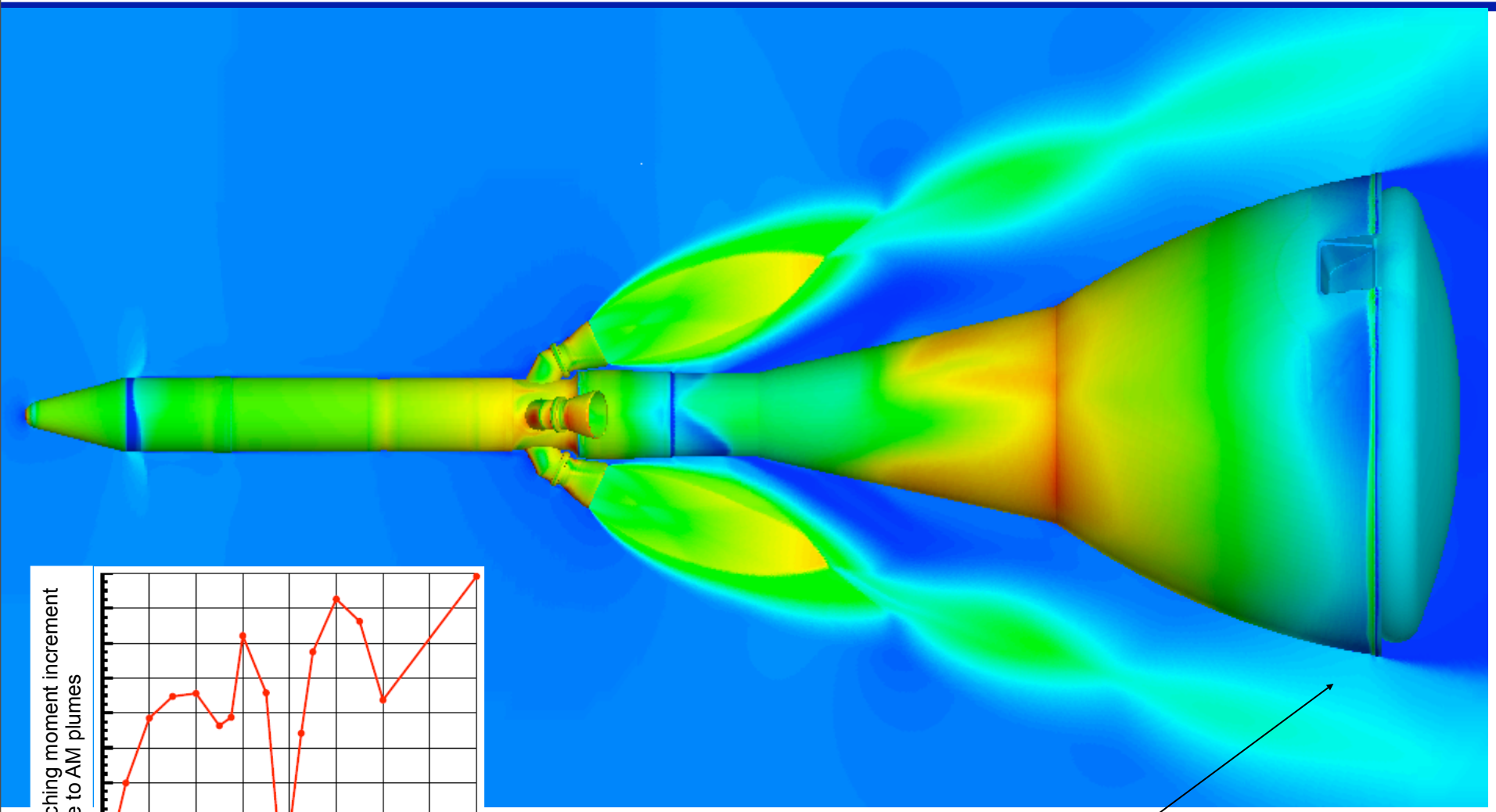
AMCT or CT = Thrust / (qbar × Sref)

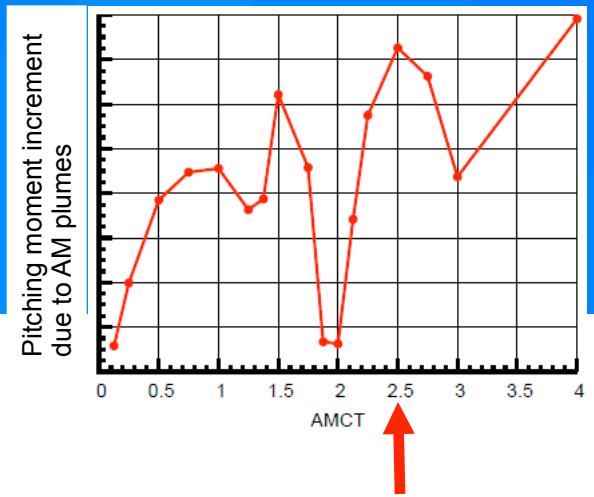
CT=2.0




Pitching moment increment due to AM plumes
0
0.5
1
1.5
2
2.5
3
3.5
4
AM CT
stable

CT=2.5

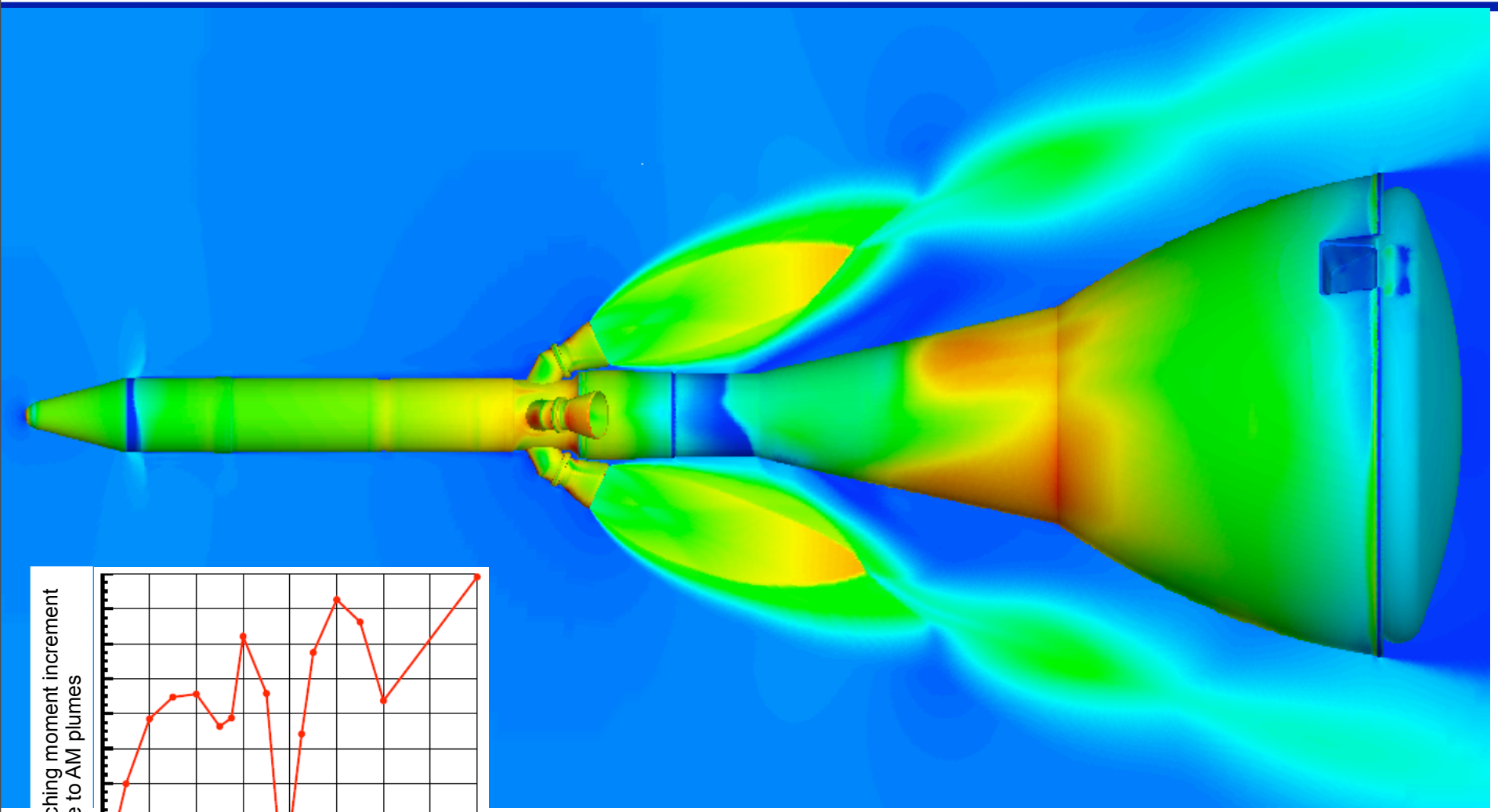


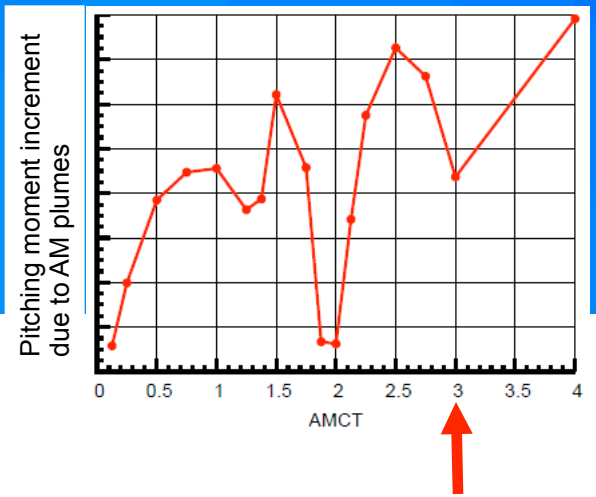


unstable

Plumes act as ejector, effect driven by plume proximity to body (CT?, alpha, growth rate)

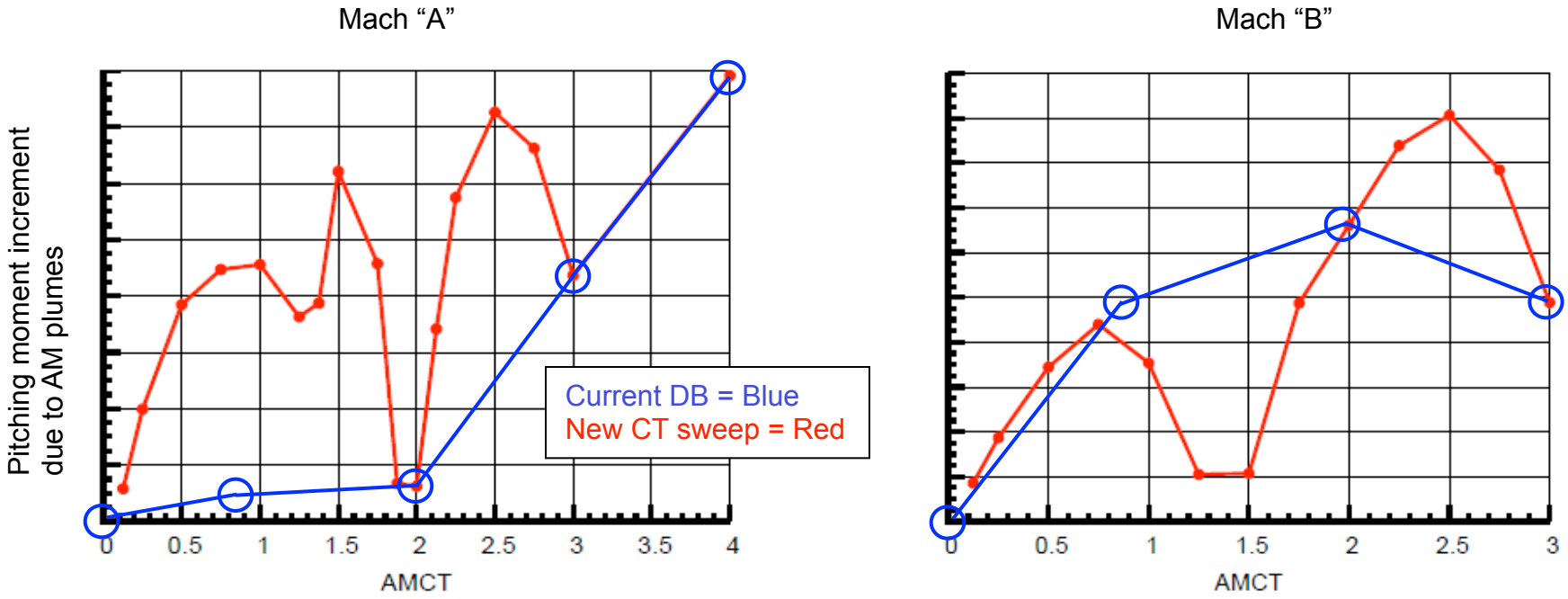
CT=3




Pitching moment increment due to AM plumes
0
0.5
1
1.5
2
2.5
3
3.5
4
AMCT

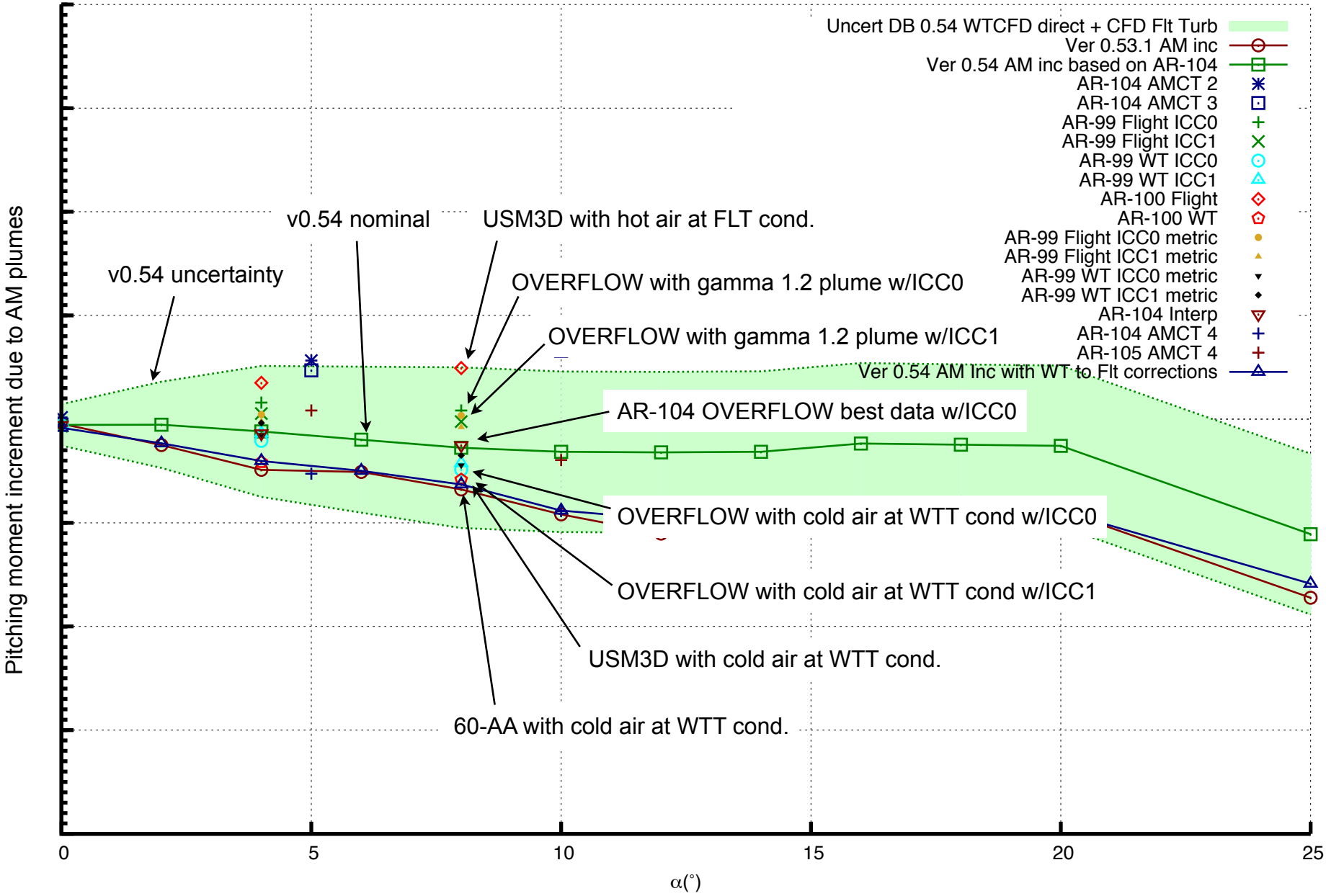
stable

AM CT discretization error



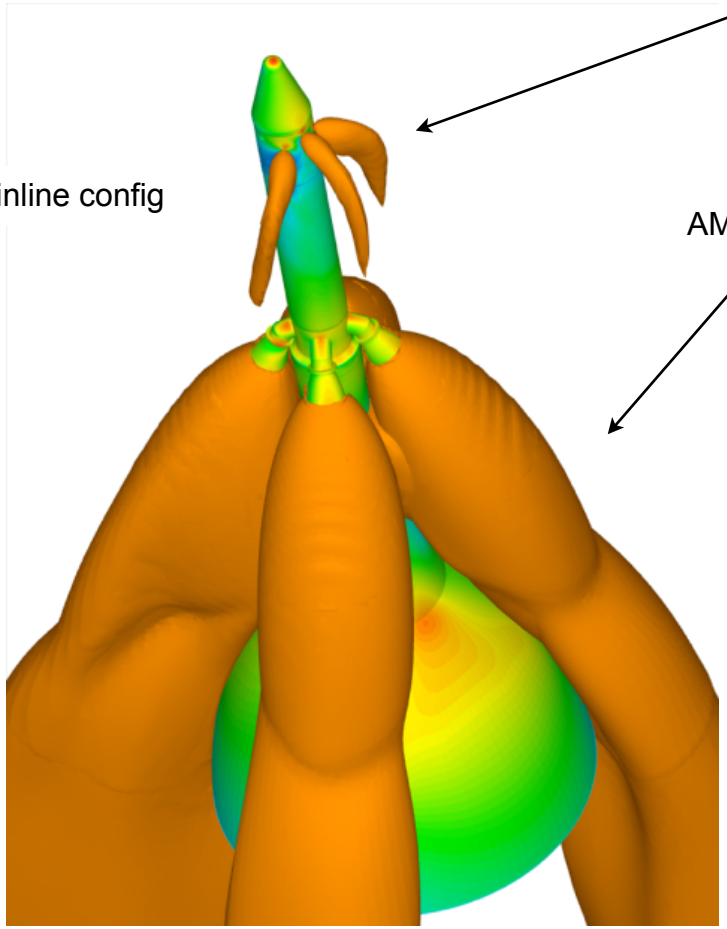
- v0.54 Database is based on AR-104 CT=2,3,4.
  - AM CT known to be non-linear, but AR-104 was over 1000 cases, 1.6 mil CPU hrs, 5+ weeks
    - Realistically need another 2x to 3x this number of cases to characterize AM CT and extend alpha to 15-20.
  - CT=0.75 inserted as interpolation point to mimic previously seen “trends” -- 75% of CT=2 value.
  - recent results run every 0.25 CT, and in some areas 0.125.
- Several points at Mach 0.9 and Mach 1.6 near CT=1.5 are ~0.025 in error from V0.54.1 prediction. Mach 1.6 is conservative, Mach 0.9 is optimistic.
- Database does not have sufficient AM CT resolution to quantify this highly non-linear effect. Limitation of resources & time.

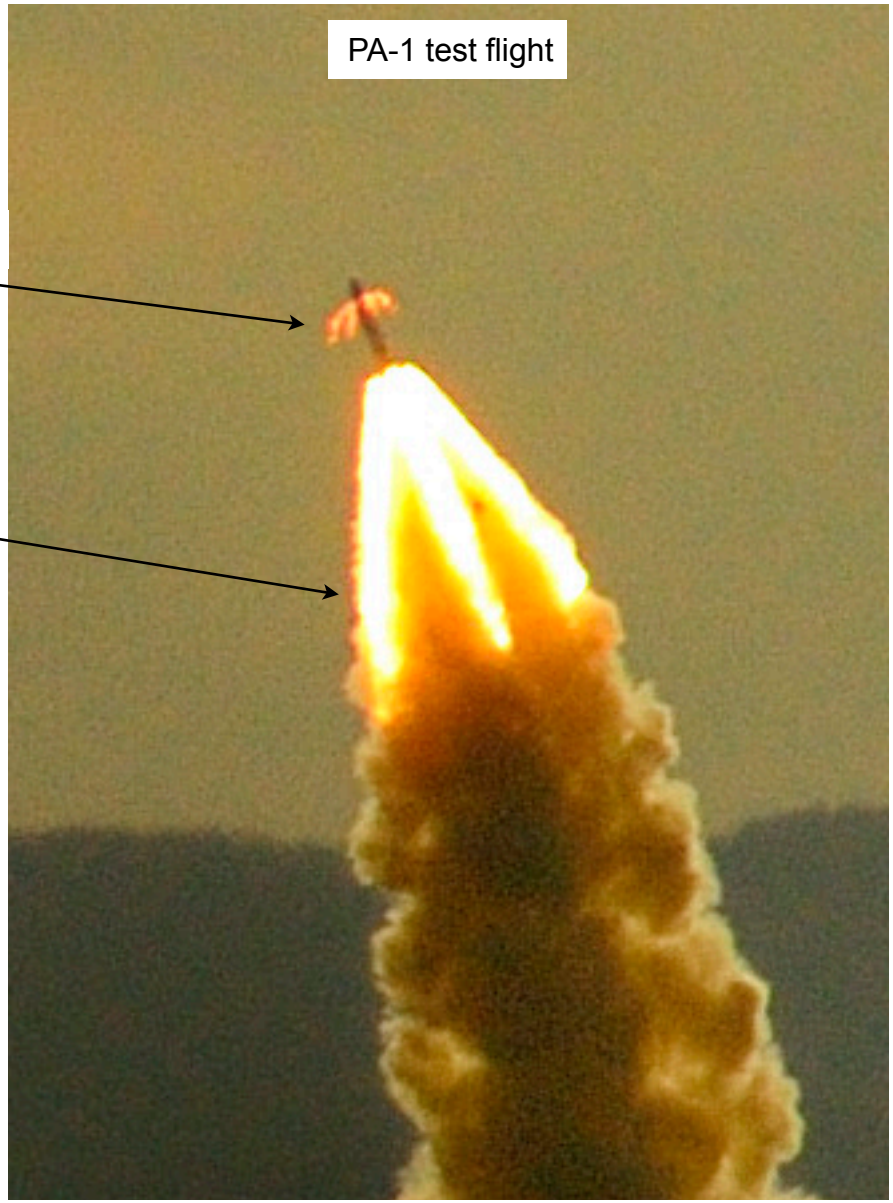
Pitching moment stability can vary from stable to unstable depending on plume modeling



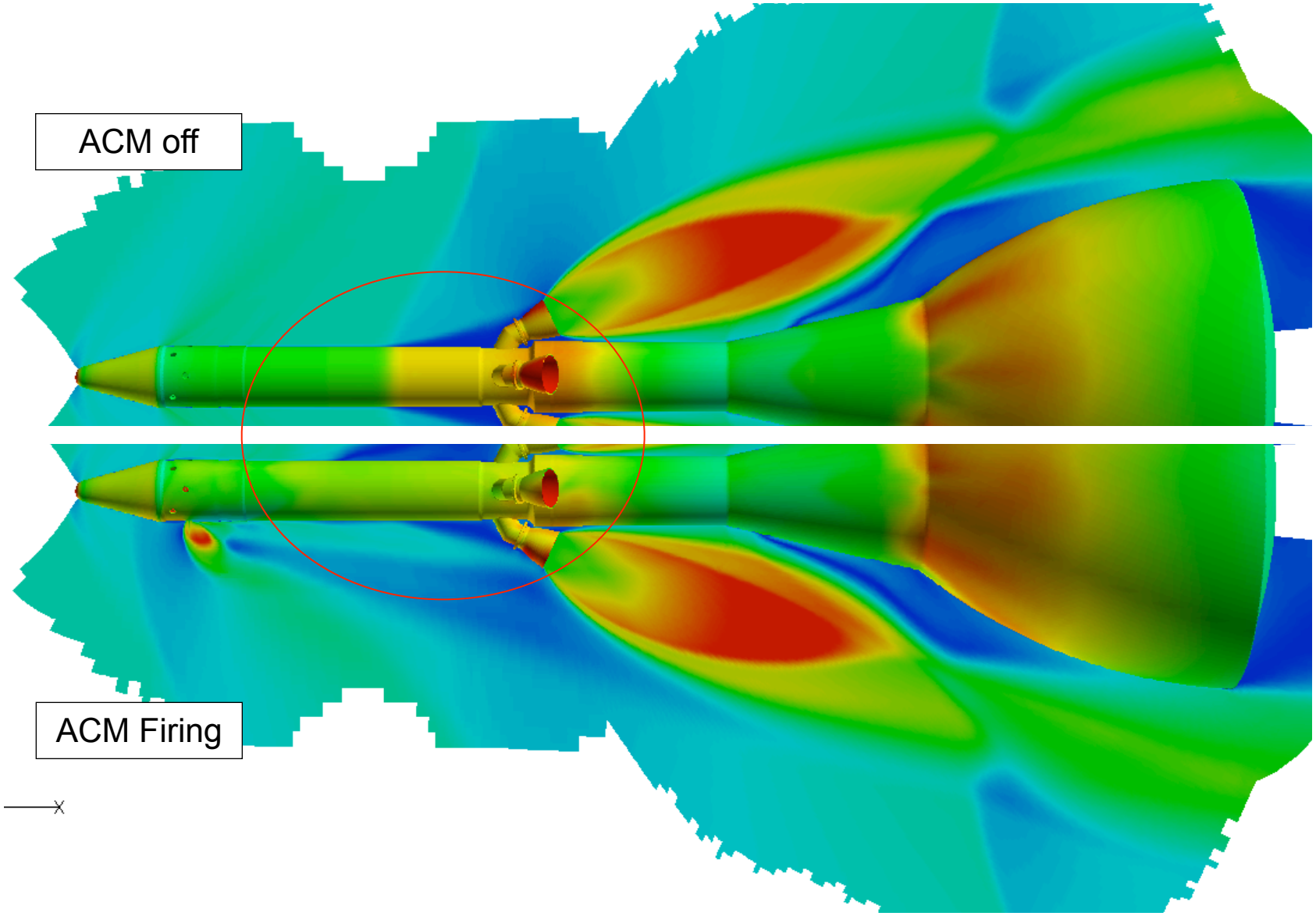
Boost Phase Plume Configuration: AM + ACM

6 to 10 plumes are in front of the vehicle at any one time





AM+ACM interaction

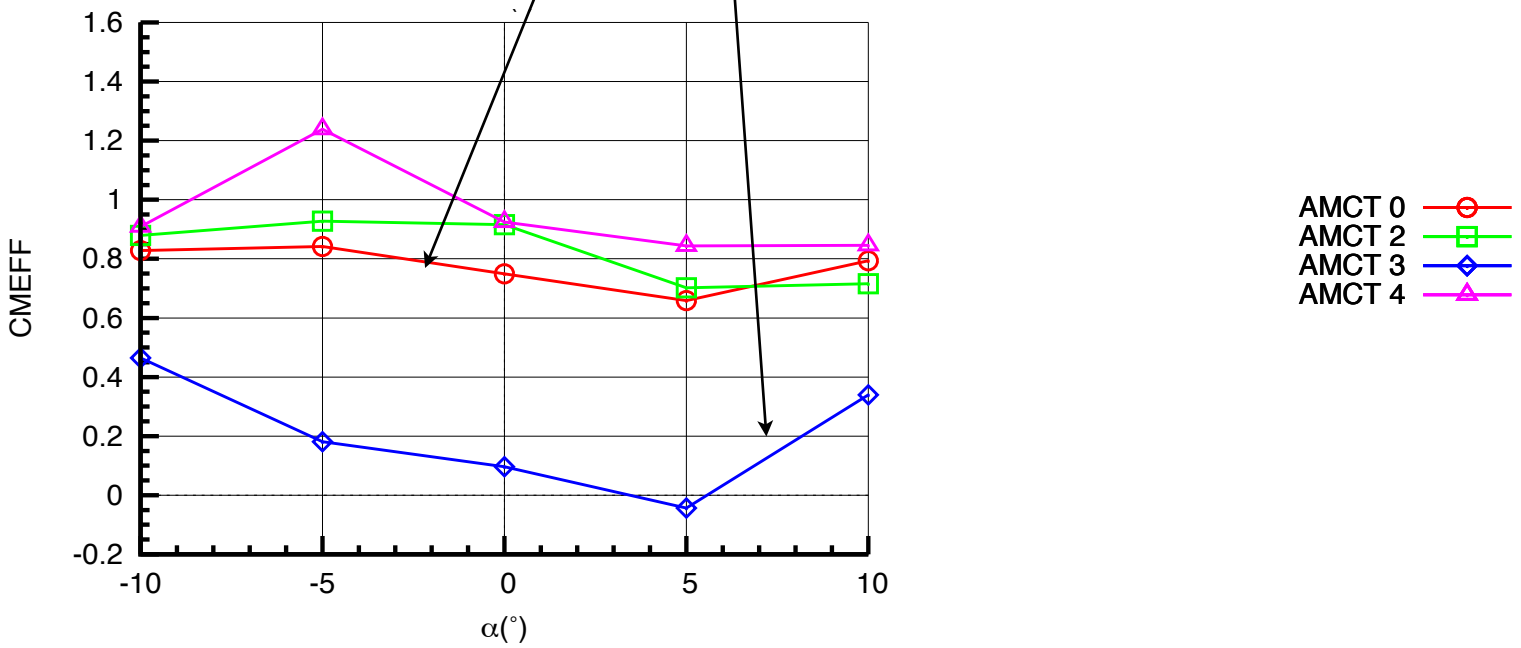


AM plume effect on ACM controllability

Observations from CFD assessment:

1. AM+ACM JI effect is more efficient than coast ACM JI case with AM plumes for AMCT of 2 and 4

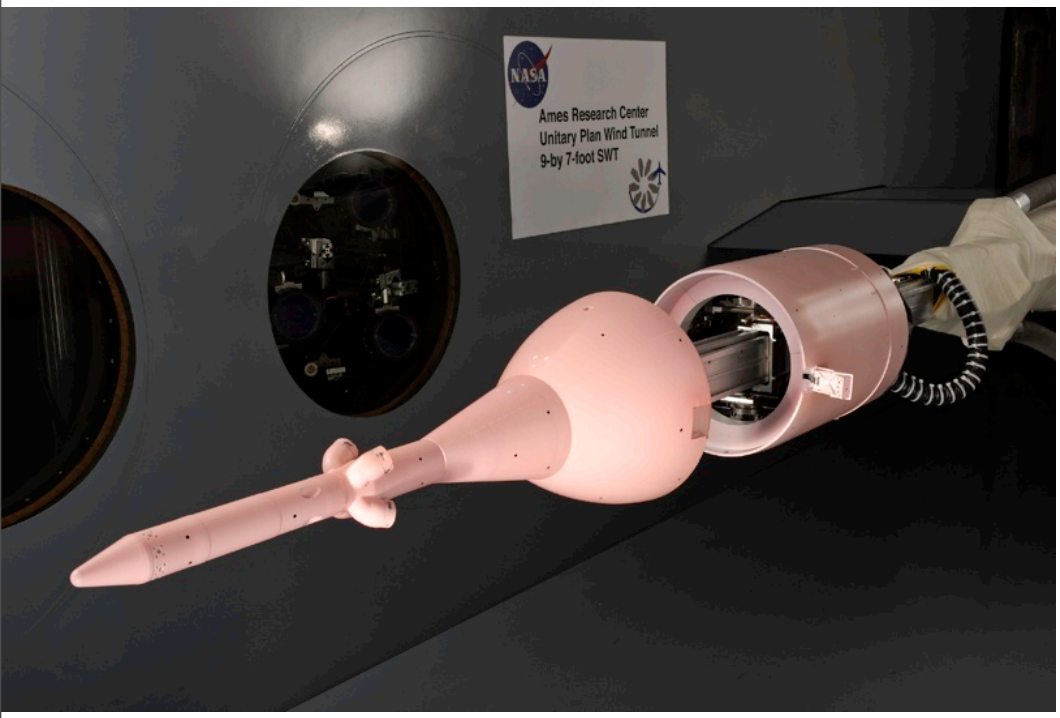
2. AM+ACM JI effects is deeply attenuating for AMCT 3



Lessons and Issues...

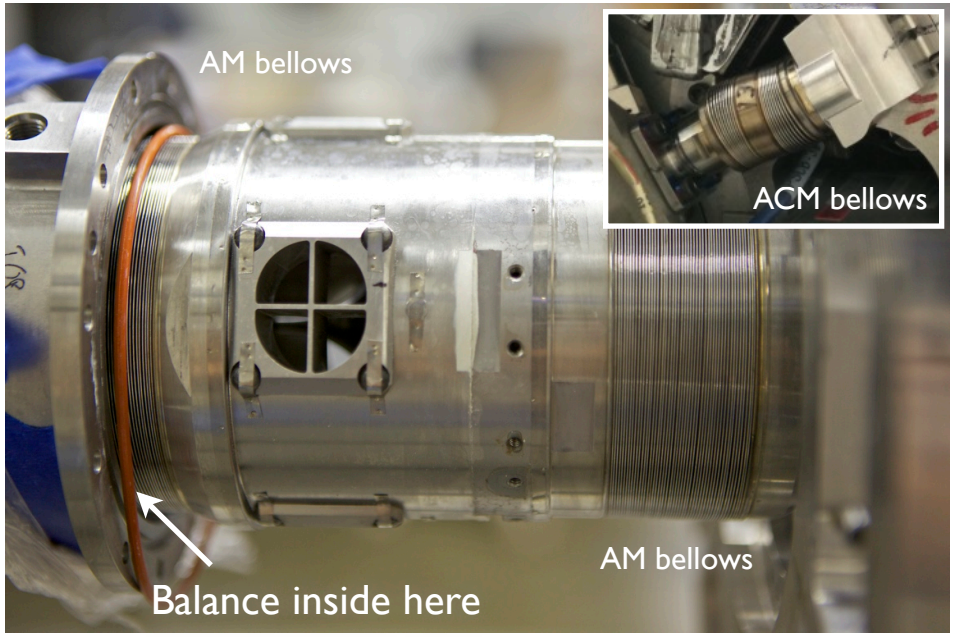
- **Confident prediction of plume aerodynamics has been very difficult for CFD, WTT and database teams**
  - 26-AA test program, the “holy grail,” was a 2.5 year quest to simulate all LAV plumes, AM and ACM plumes, and separation simultaneously
    - Design using multiple bellows viewed as the only way to measure fully metric jet interaction with enough accuracy
      - Led us down the path of 18 months of bellows technology development
    - Used CFD to scale cold air plumes to match CFD based hot plume force and moment results (gamma x M^2 for transonic and gamma x M^2/beta for supersonic)
  - CFD simulation of plume aero within CAP is at a detente
    - Current OVERFLOW grid density is on the order of 50 to 80 million and believed to be the optimum number for accuracy vs productivity
      - 5000 to 10,000 OVERFLOW and USM3D CFD solutions have bee completed
    - Turbulence model studies shows that OVERFLOW SST model is the best model, but not perfect as plume flowfield data comparison shows experimental answer is in-between having compressibility corrections on or off
    - Solid rocket motor plume data on mainline config at transonic conditions unavailable
  - Database team built 9 dimensional database with sparse data sets
    - Includes uncertainties on all components for abort plume aero

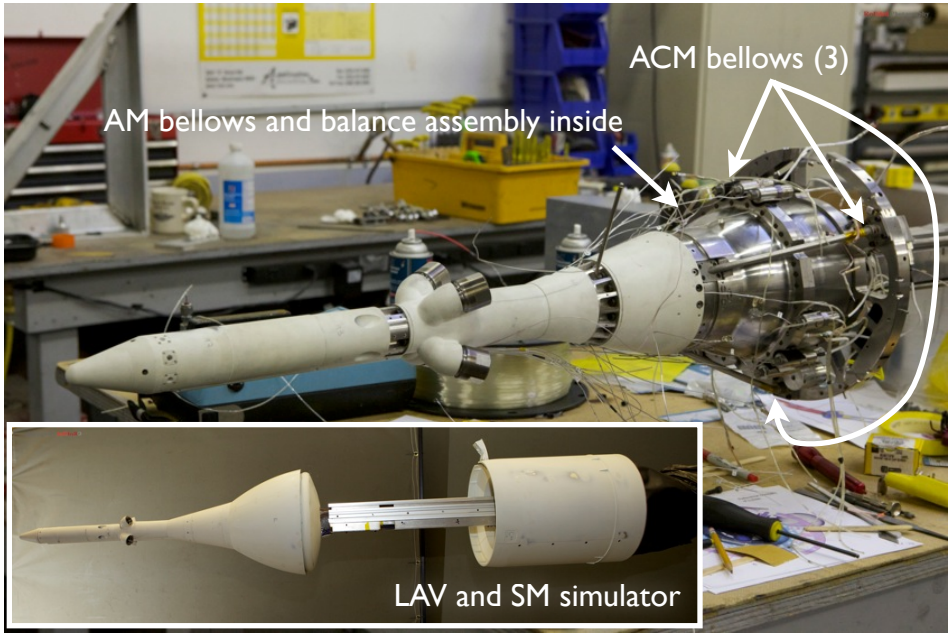
26-AA: the Holy Grail Wind Tunnel Test



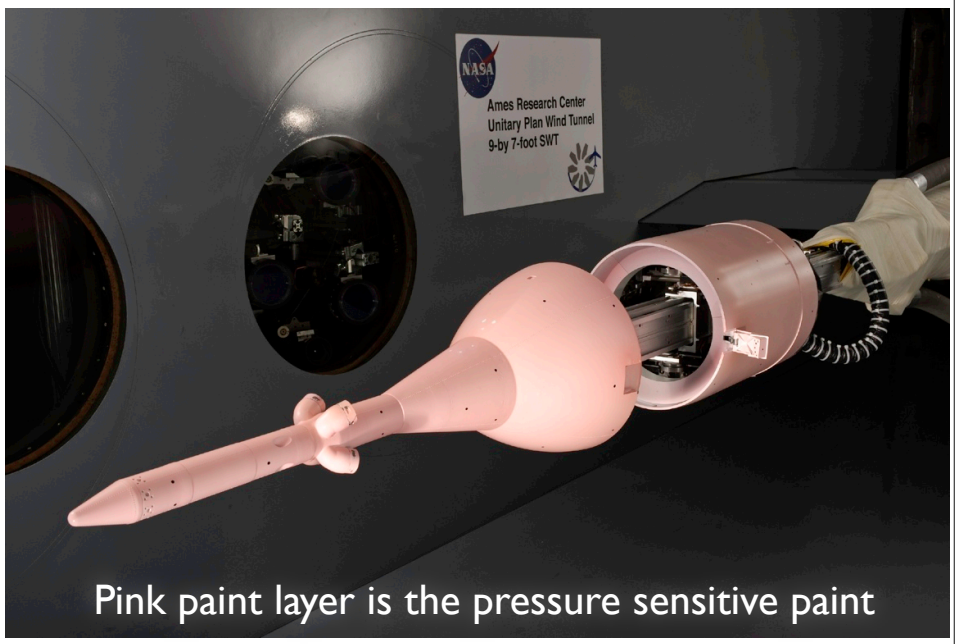
The 26-AA wind tunnel test obtained AM plumes and ACM plumes data simultaneously using cold air for transonic to supersonic Mach conditions at a variety of thrust ratio conditions.

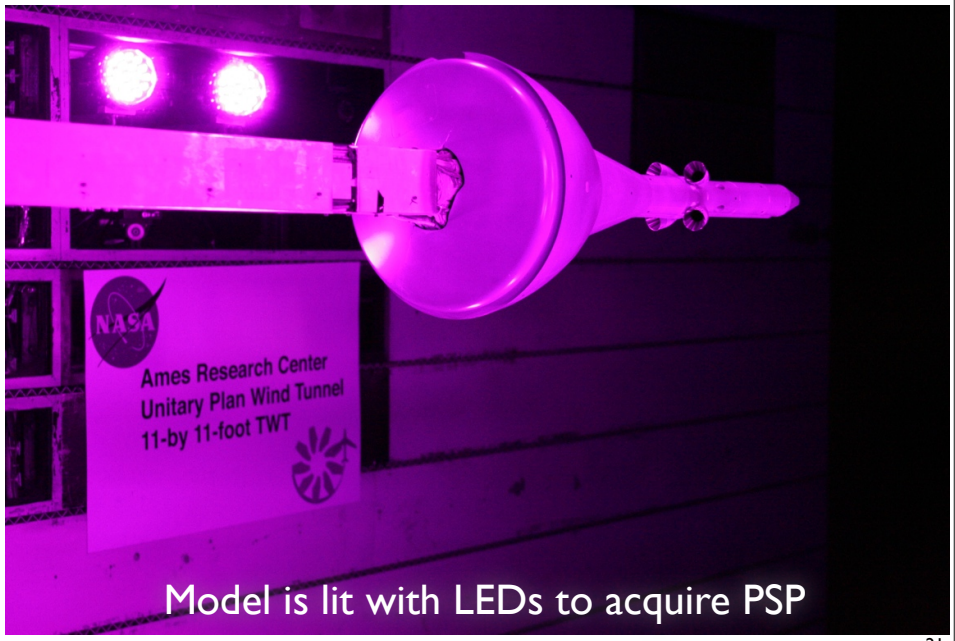
26-AA Balance and Bellows



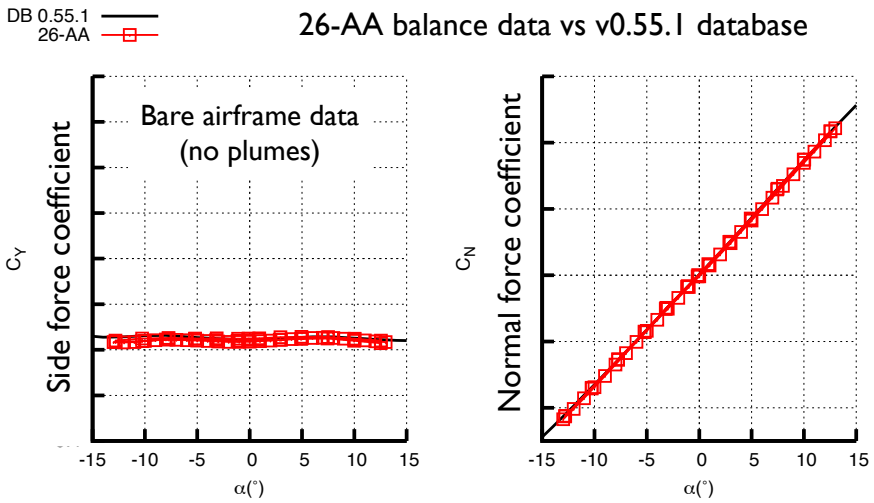


26-AA Pressure Sensitive Paint

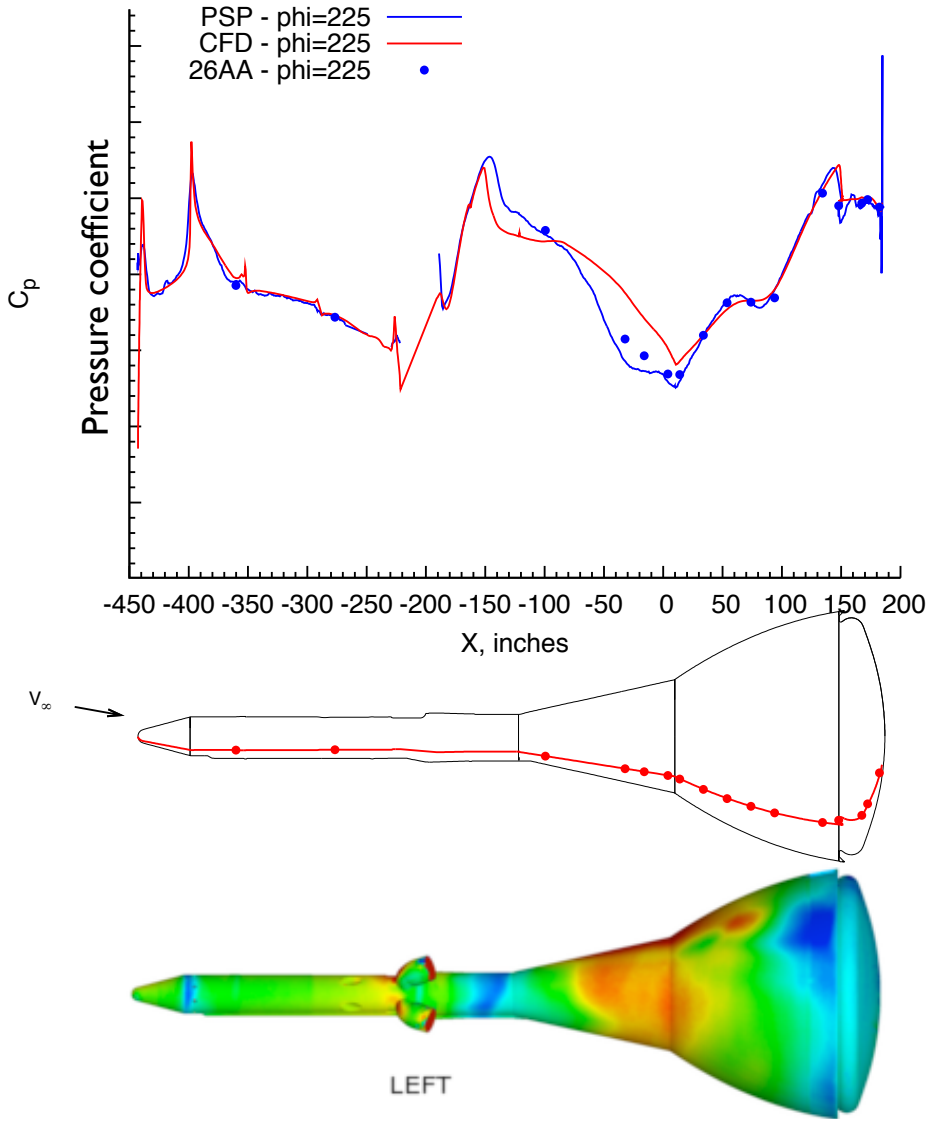




Balance Data

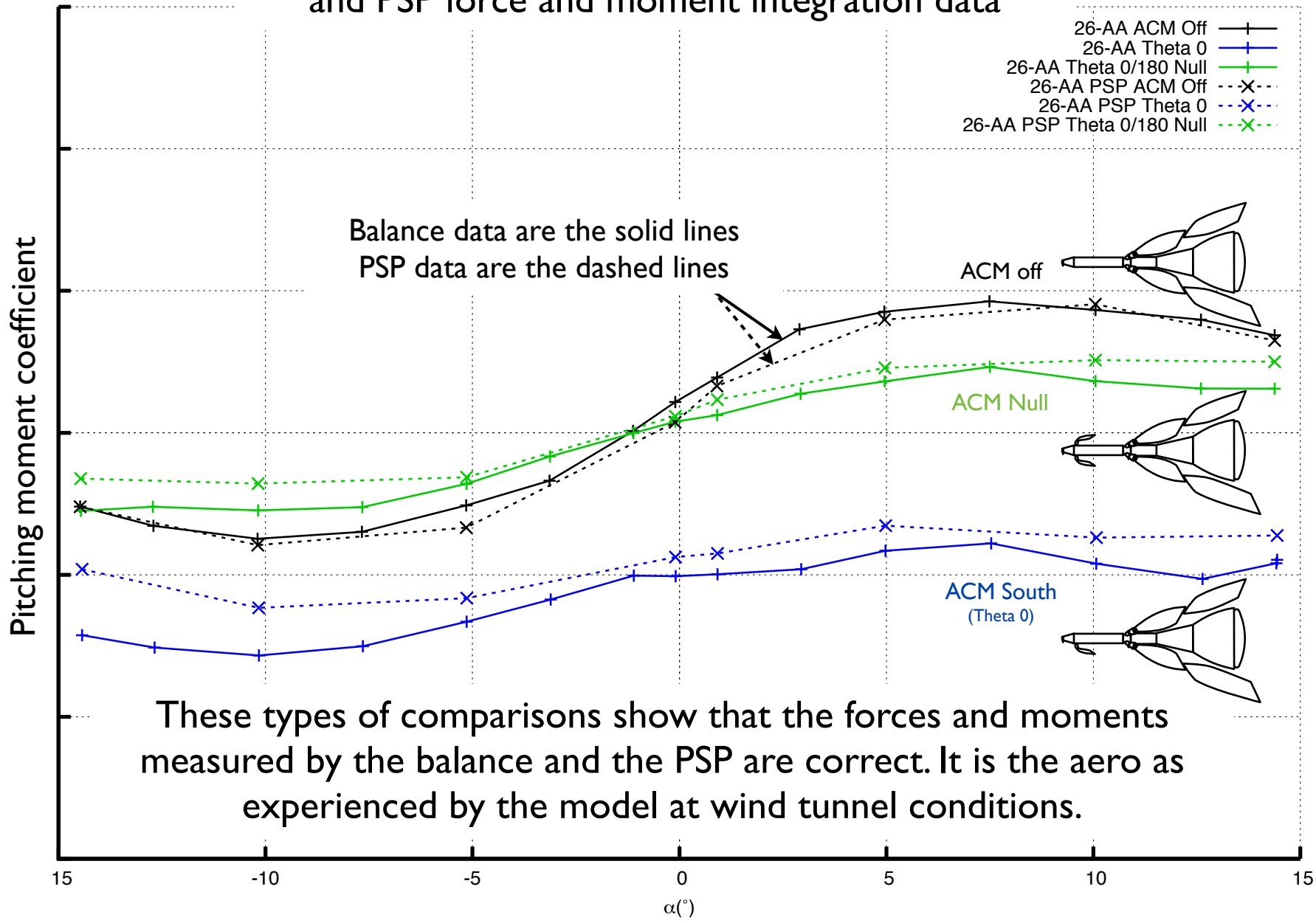


PSP data



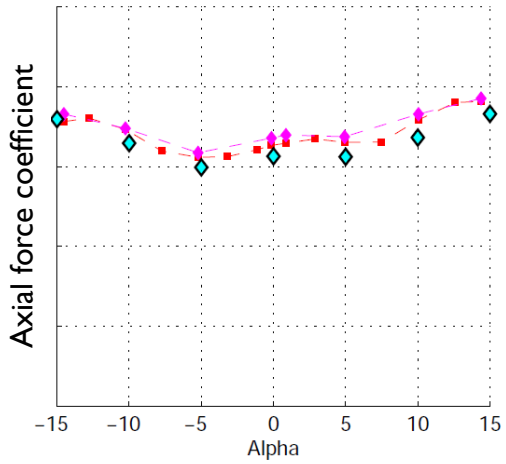
Static surface pressure data from PSP can be integrated over OML to develop force and moment coefficients for comparison to balance data

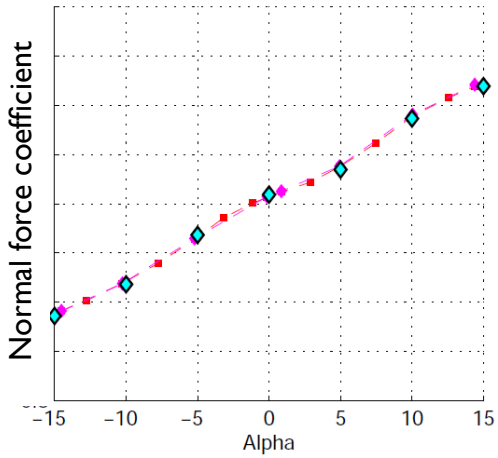
Generally good agreement between balance data and PSP force and moment integration data

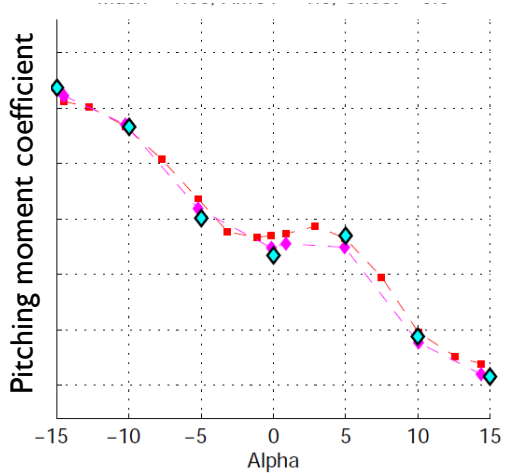


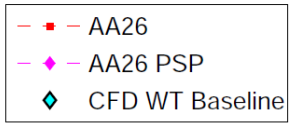
These types of comparisons show that the forces and moments measured by the balance and the PSP are correct. It is the aero as experienced by the model at wind tunnel conditions.

Generally, CFD at WTT conditions match F&M coefficient test data well for AM JI aero configurations (no ACM)

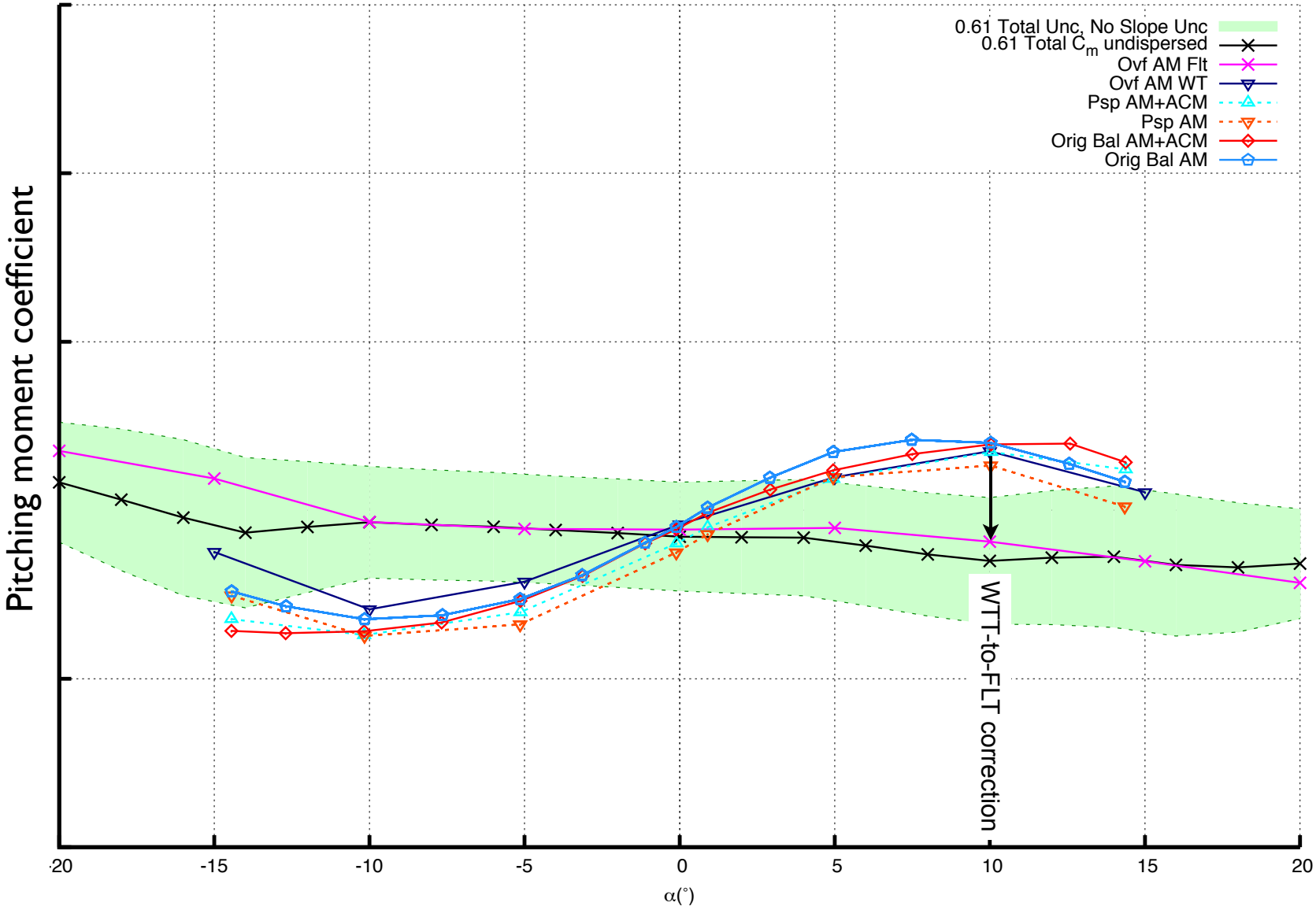




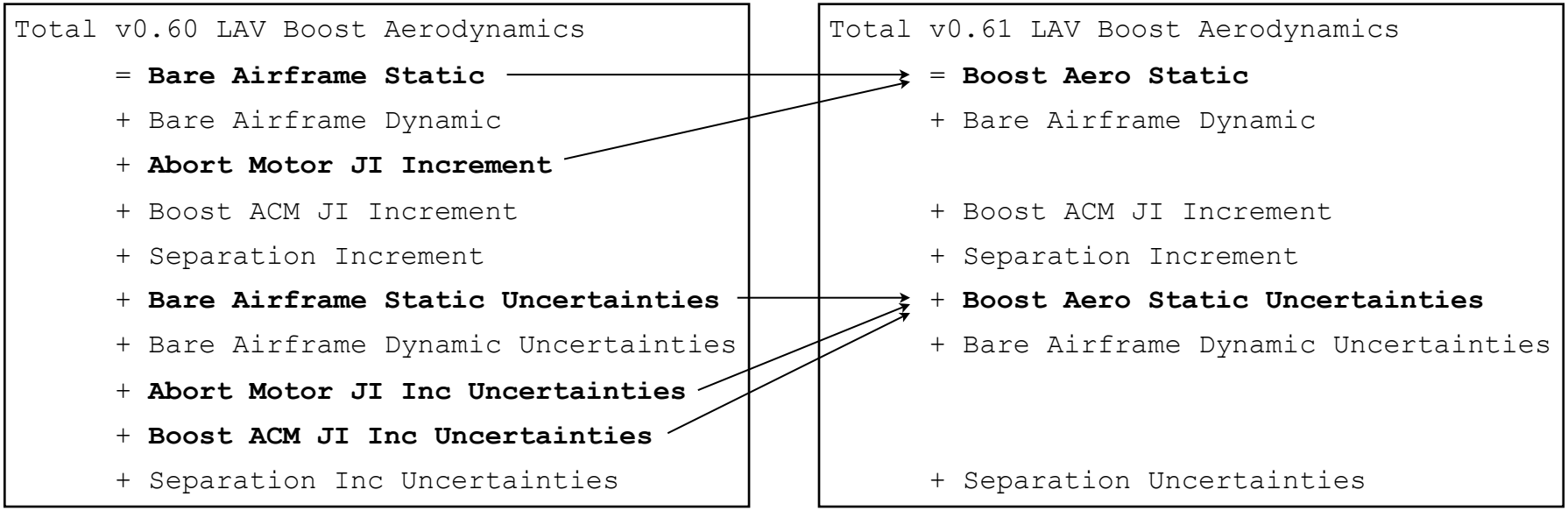




Excellent comparison between CFD to 26-AA test data enabled wind tunnel to flight correction for hot plume, geometry and Reynolds effects.

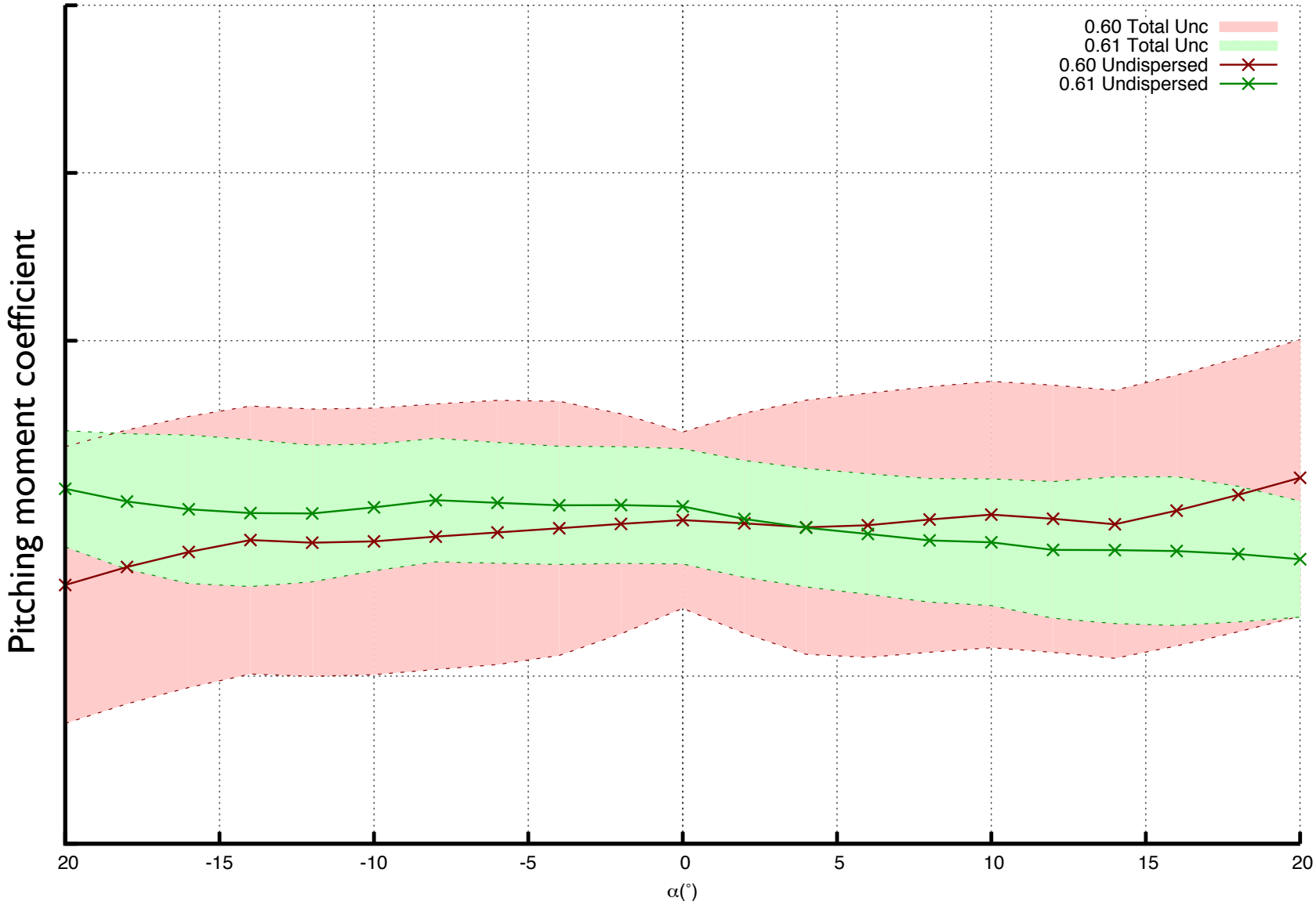


Boost Phase Model changes in v0.61



- Boost aero from v0.60 and prior databases was a buildup of unpowered bare airframe static aero and uncertainties plus AM JI, ACM JI and Separation increments and increment uncertainties
  - Static aero, increments and uncertainties were from different sources (CFD, 83-AA, 60-AA, 75-AA)
- Data from 26-AA enabled creation of combined models not possible before
  - Static and AM JI environments can be combined into one
  - More detailed ACM JI increments
  - Static, AM JI and ACM JI uncertainties can be combined into one
  - Expected benefits are more accurate nominal prediction and smaller uncertainties

26-AA enabled a reduction in the number of components for boost phase aero, and therefore, a reduction in uncertainties



Recommendations

- **Design recommendations for tractor-type launch configurations**
  - For prototyping type studies, it is advisable to obtain as dense as possible thrust ratio conditions, be it CFD or WTT tools
  - Place the plumes as far aft as possible to try to minimize non-linear aero with plume shape
  - Best option appears to be direct flow type abort motor design which puts CG location in more favorable position
  - To a man, no one within CAP wants to deal with ACM or AM+ACM plume aero
  - To a man, no one wants to deal with bellows
- **Within CAP, we're at a technological impasse or nearly so**
  - I believe we've gone as far as we can go with cold air for WTT
  - I believe we've gone as far as we can go with 2 species CFD
  - For next steps, we have to get flight level data
    - Accurate SRM gas plumes in a crossflow (WTT, Flight)
    - Accurate LAV AM+ACM JI hot gas data (WTT, Flight)
    - Higher fidelity and higher production CFD capability (multi-phase, chemistry, etc)
  - Uncertainties...

Cultural points for Aerodynamics Teams

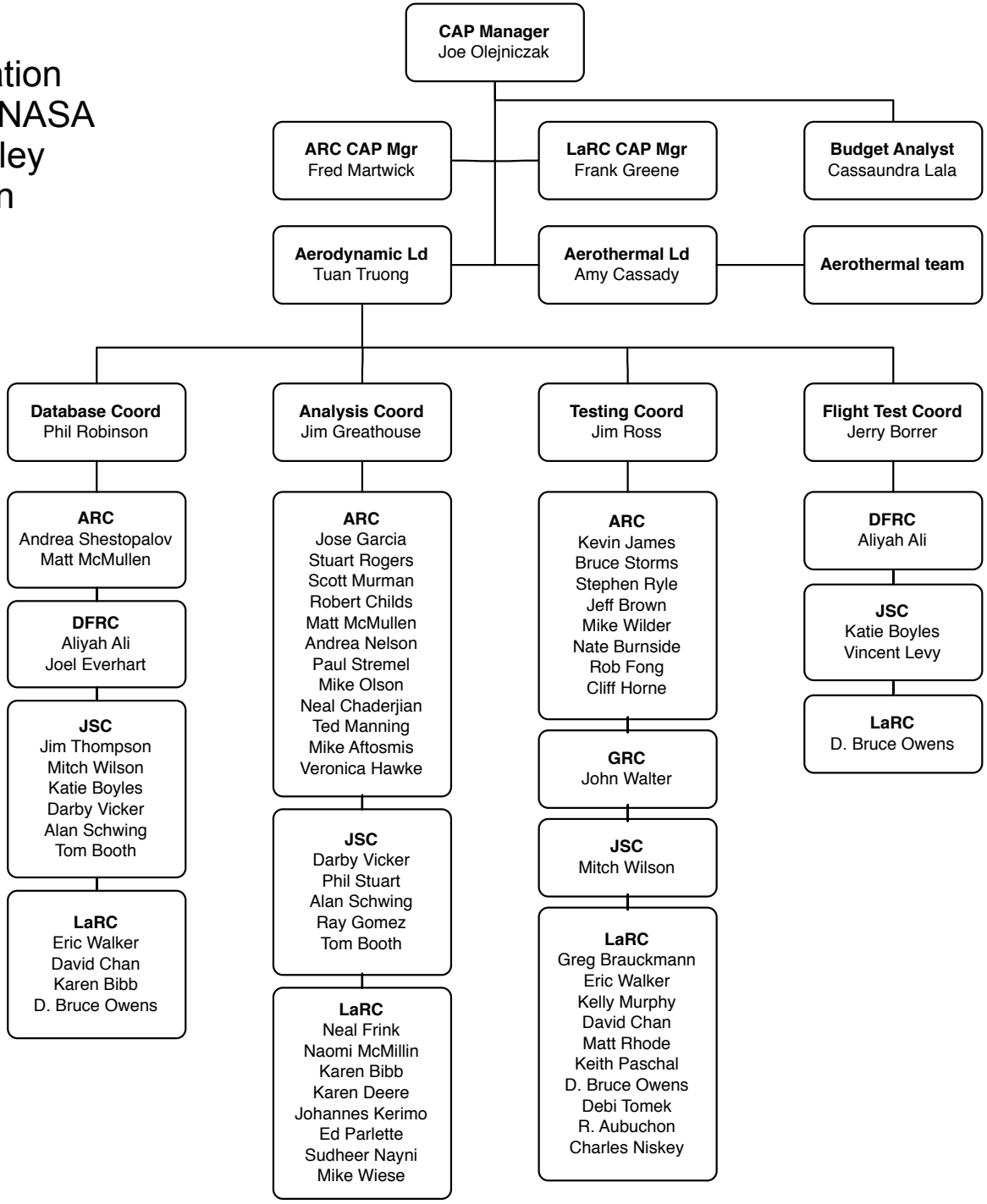
- **Cultural**
  - Being Aerodynamicists versus CFD analysts or WTT engineers or Uncertainty specialists - we need more aerodynamicists
  - Aerodynamics should not simply be “environments” or “analytics” for the Project or Program, but should be a subsystem that participates in the design process
    - Observation: Constellation has too many engineers, not enough designers
- **Using the right tools for the right job**
  - CFD is good for early configuration trades (capsules versus lifting bodies versus wings)
  - For a Project or Program needing an aerodynamic database, WTT is still required, and CFD should be used in appropriate places
- **Uncertainty and monte carlo analysis process**
  - The process is very uncomfortable - fix it?
  - Each individual has their own judgment on acceptable uncertainty levels and dispersion processes

Issues & Lessons

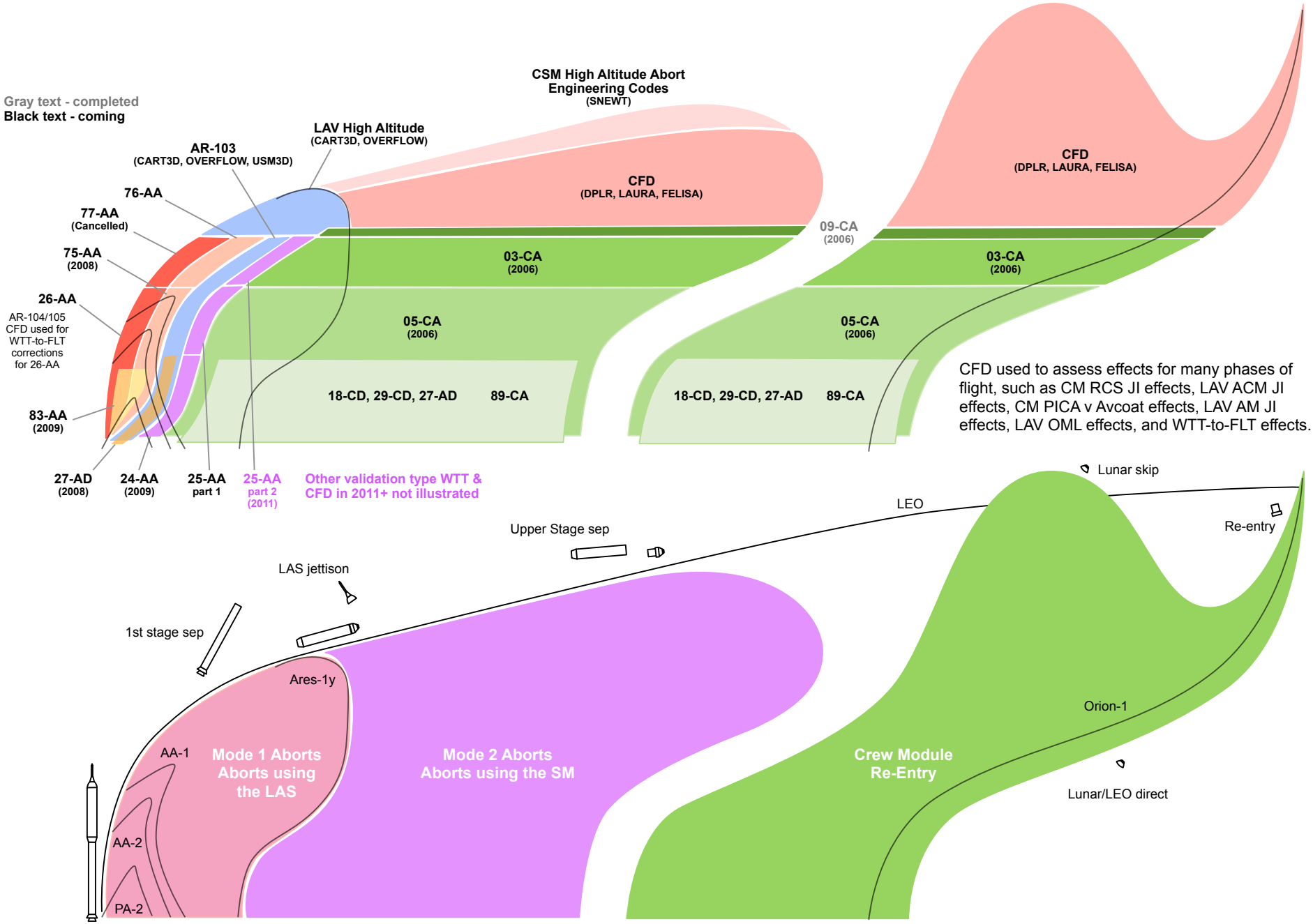
- **In the beginning, we over-estimated how good CFD would be at database development and we under-estimated how non-linear transonic boost phase jet interaction aero would be**
  - CFD is currently not productive enough to generate enough data to develop a subsonic, transonic and supersonic database for non-trivial configurations
    - By necessity, CAP did use CFD, but had to use a lot symmetry assumptions
    - Lack of data decreases the understanding of the aerodynamics, decreases confidence in how good the database is, makes the aerodynamic database hard to defend, and makes it hard to be participants in the design process
  - Our experience and judgement on jet interaction aerodynamics for tractor-type LAS was really a blank slate - we didn't have much
    - The mainline Orion LAV configuration is not like Apollo with the addition of the ACM, different cant angle (25° vs 35°), and different OML
    - The nonlinear nature of AM and AM+ACM jet interaction meant we needed a whole lot more data then we were capable of producing and decreased team's confidence in our predictions
- **My contention would be that for aerodynamic database for a fore-body plume-dominated blunt-body configuration, you should run a thorough test program as early as possible (SRR or prior)**

Backup

CAP is a NASA wide organization with major contributions from NASA Ames Research Center, Langley Research Center and Johnson Space Center.

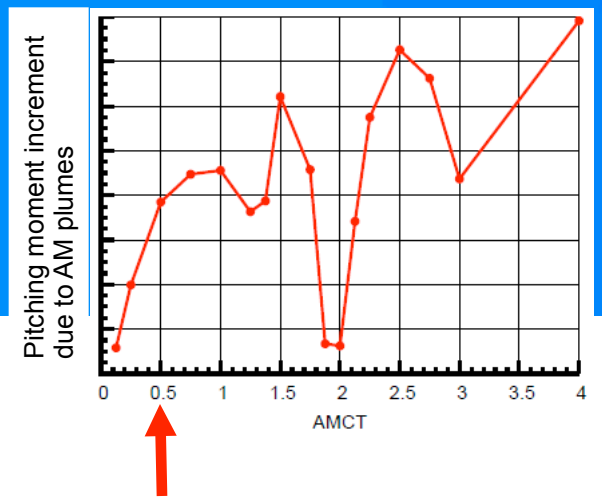


High level CAP aerodynamic task map for Orion Aero



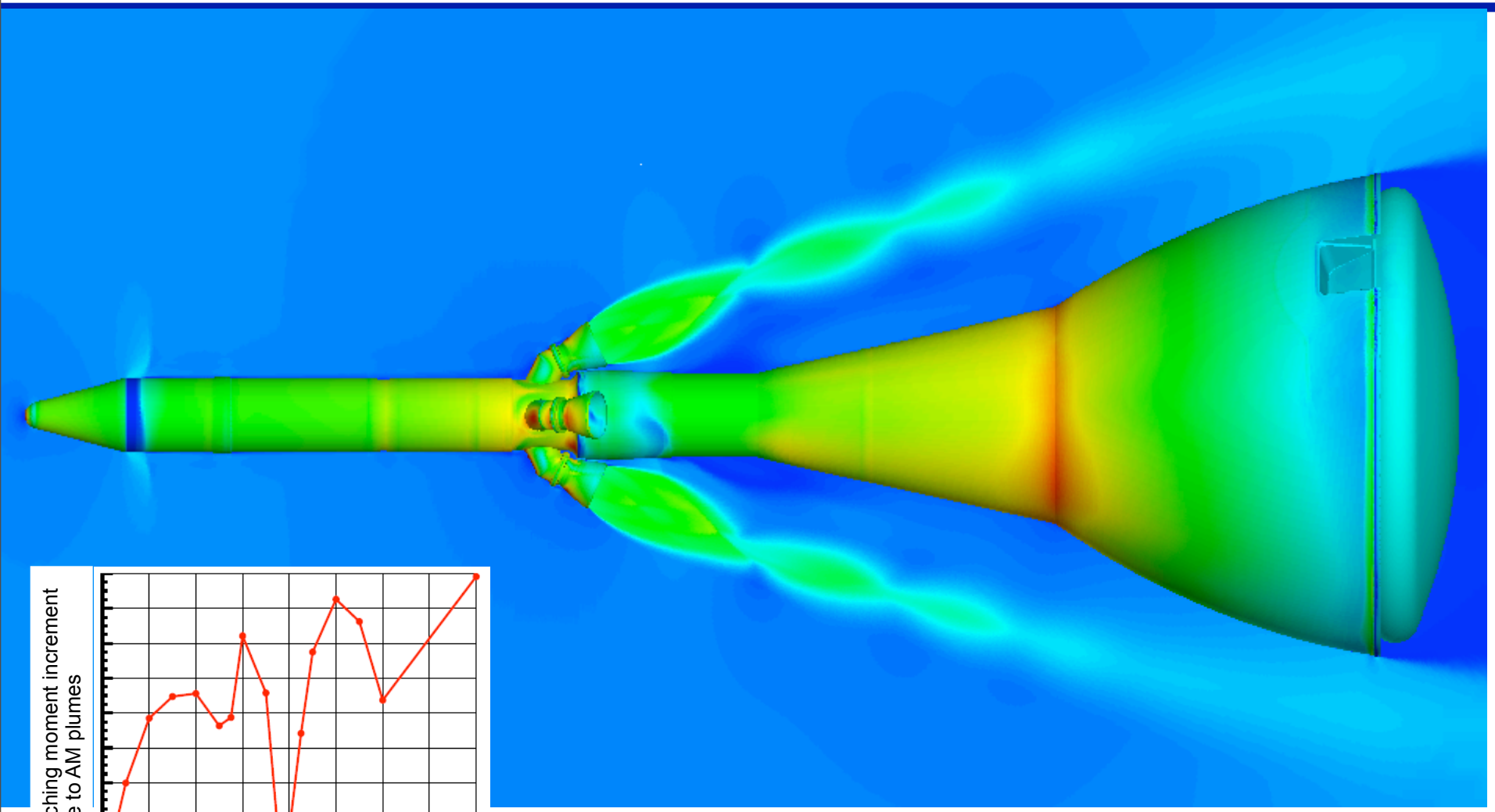
CT=0.5

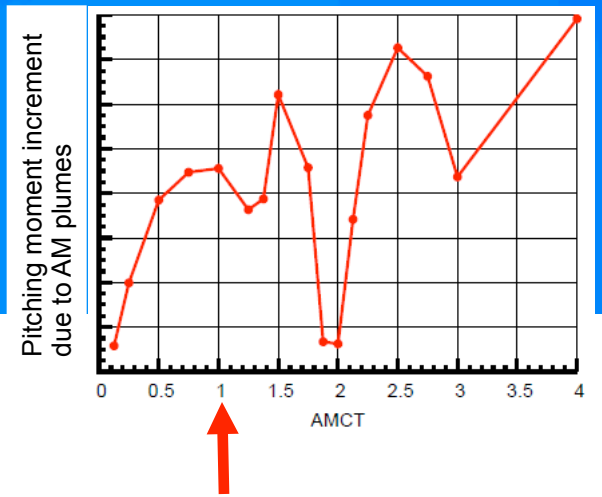
OVERFLOW CFD results



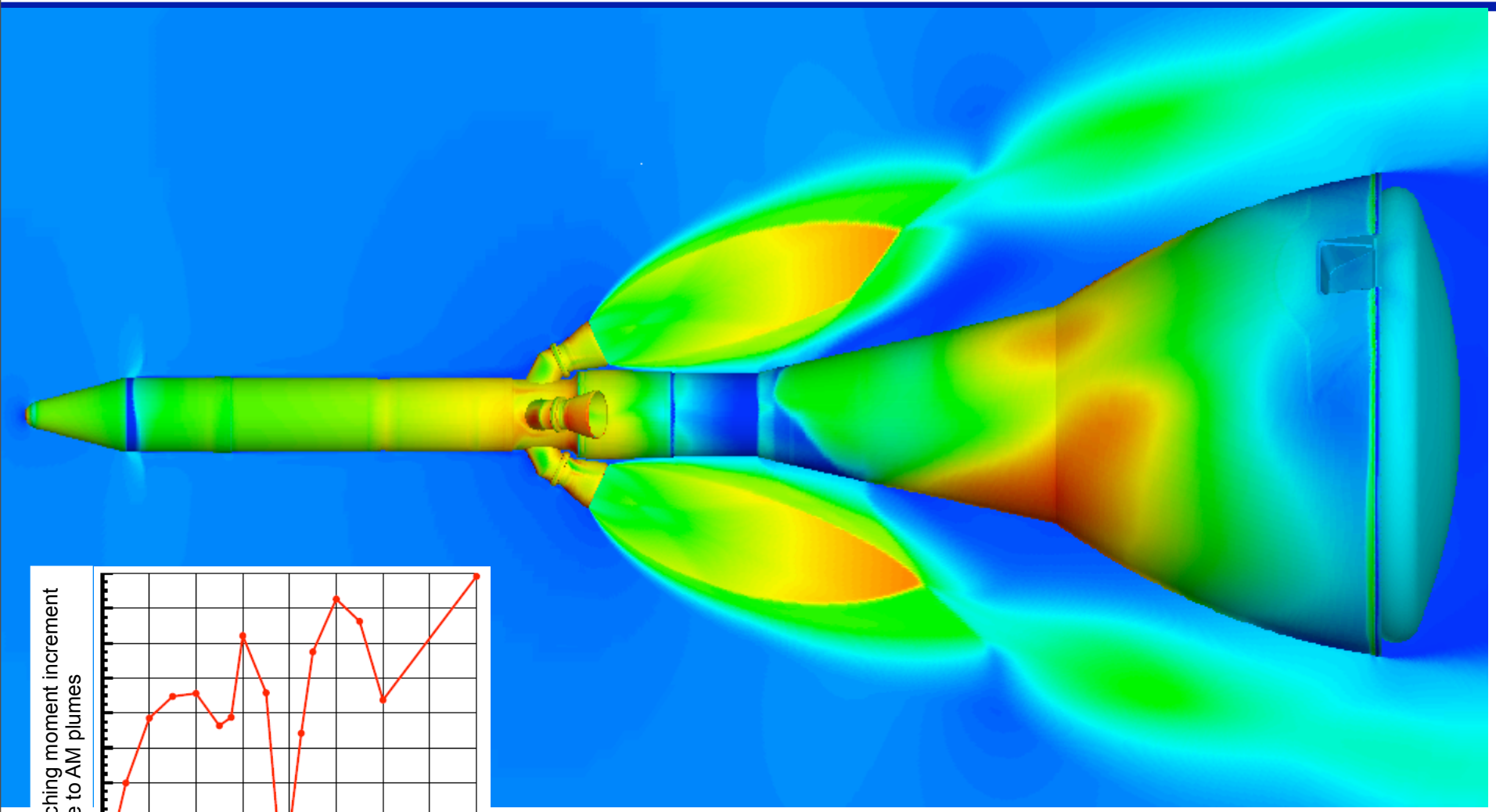
AMCT or CT = Thrust / (qbar × Sref)

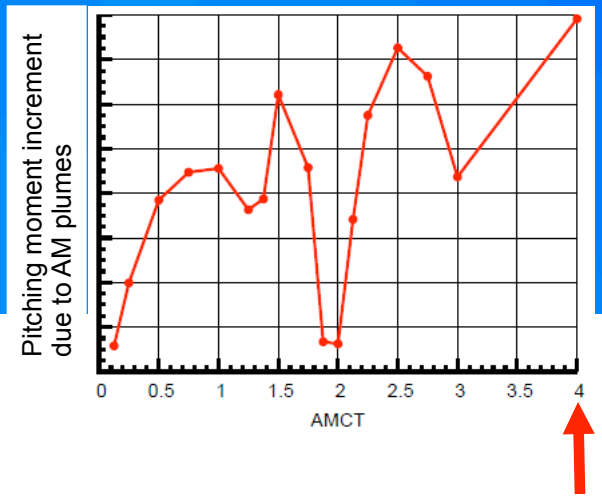
CT=1.0



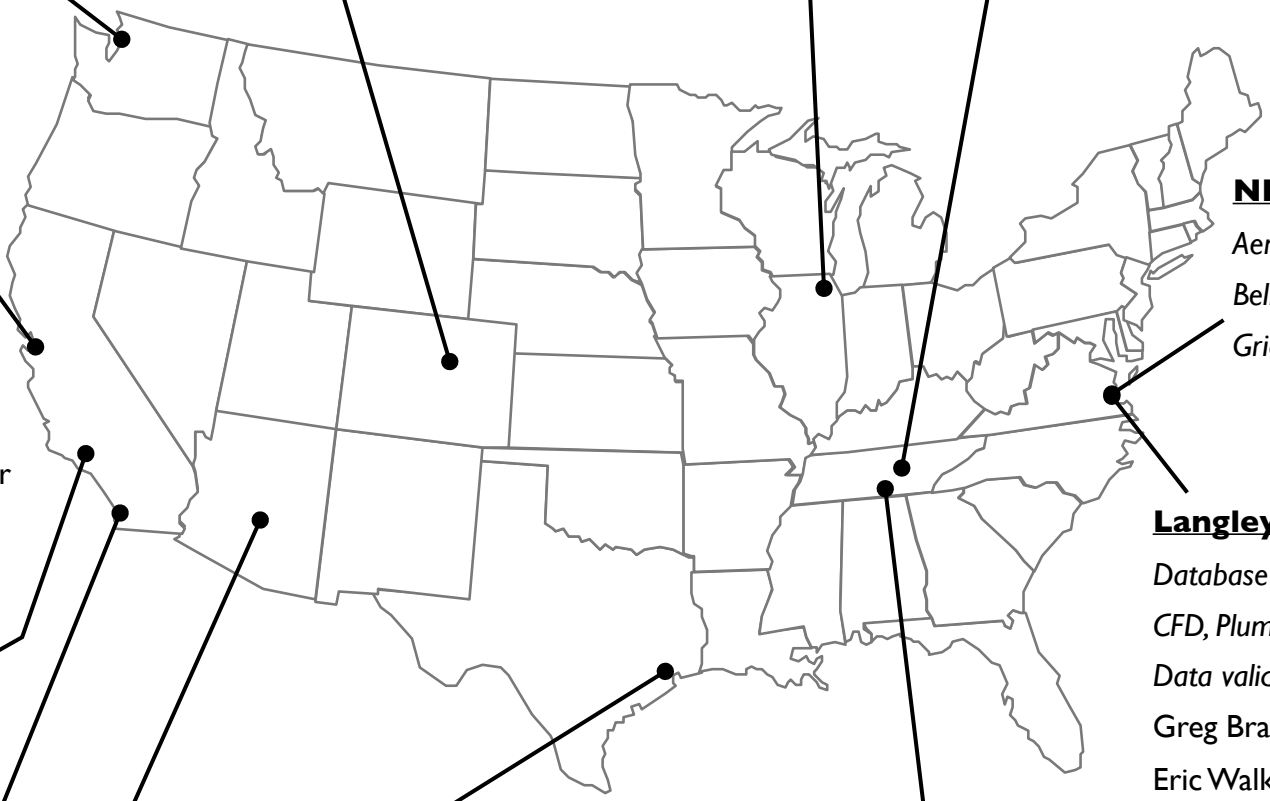

Pitching moment increment due to AM plumes
0
0.5
1
1.5
2
2.5
3
3.5
4
AMCT

CT=4




Pitching moment increment due to AM plumes
0
0.5
1
1.5
2
2.5
3
3.5
4
AMCT
unstable

26-AA and v0.61 Database Acknowledgements



Patterson Labs

LAV model fab

Single piece bellows

Lockheed Martin

Test and database support

Dave Mayfield, Jared Cross, Brian Jones

Duraflex

Edgewelded bellows

Flexial

Edgewelded bellows

Ames

Test management

Test DDT&E, CFD

SM, sting model fab

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Bruce Storms, Stephen Ryle

Don Morr, Steve Buchholtz

Louise Walker, Laura Kushner

James Bell, Fred Martwick

Bob Childs, Matt McMullen

Model Shop, UPWT Facility

NESC

Aero Peer review

Bellows review

Grid fins

Langley

Database Development

CFD, Plume modeling

Data validation

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David Chan

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Dryden

Test support

Aliyah Ali

Triumph Aerospace

Balance calibration

Dennis Booth

Orbital

Service module/ATB

Mike Jeffries

Johnson

Database Development, CFD, Data validation

Phil Robinson, Jim Greathouse

Darby Vicker, Tom Booth, Alan Schwing

Molly White, Mitch Wilson, Jim Thompson

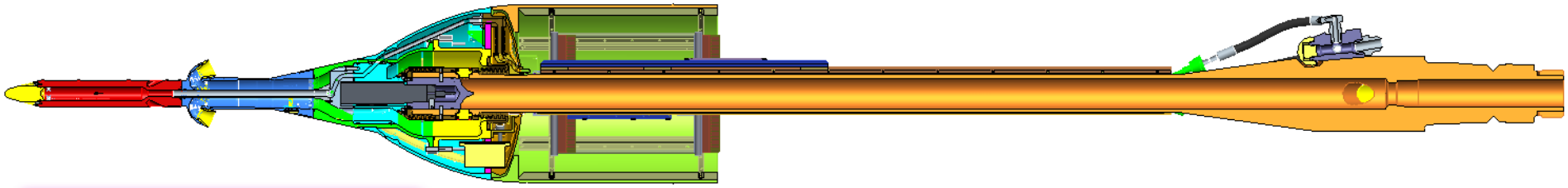
AEDC

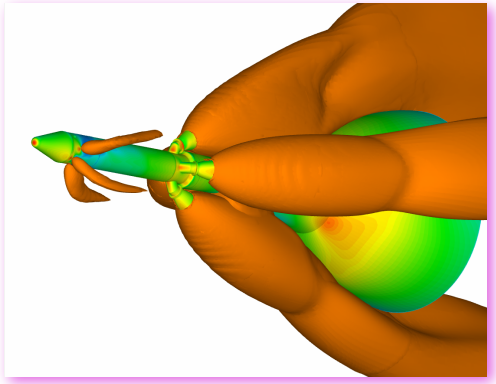
Pressure Sensitive Paint

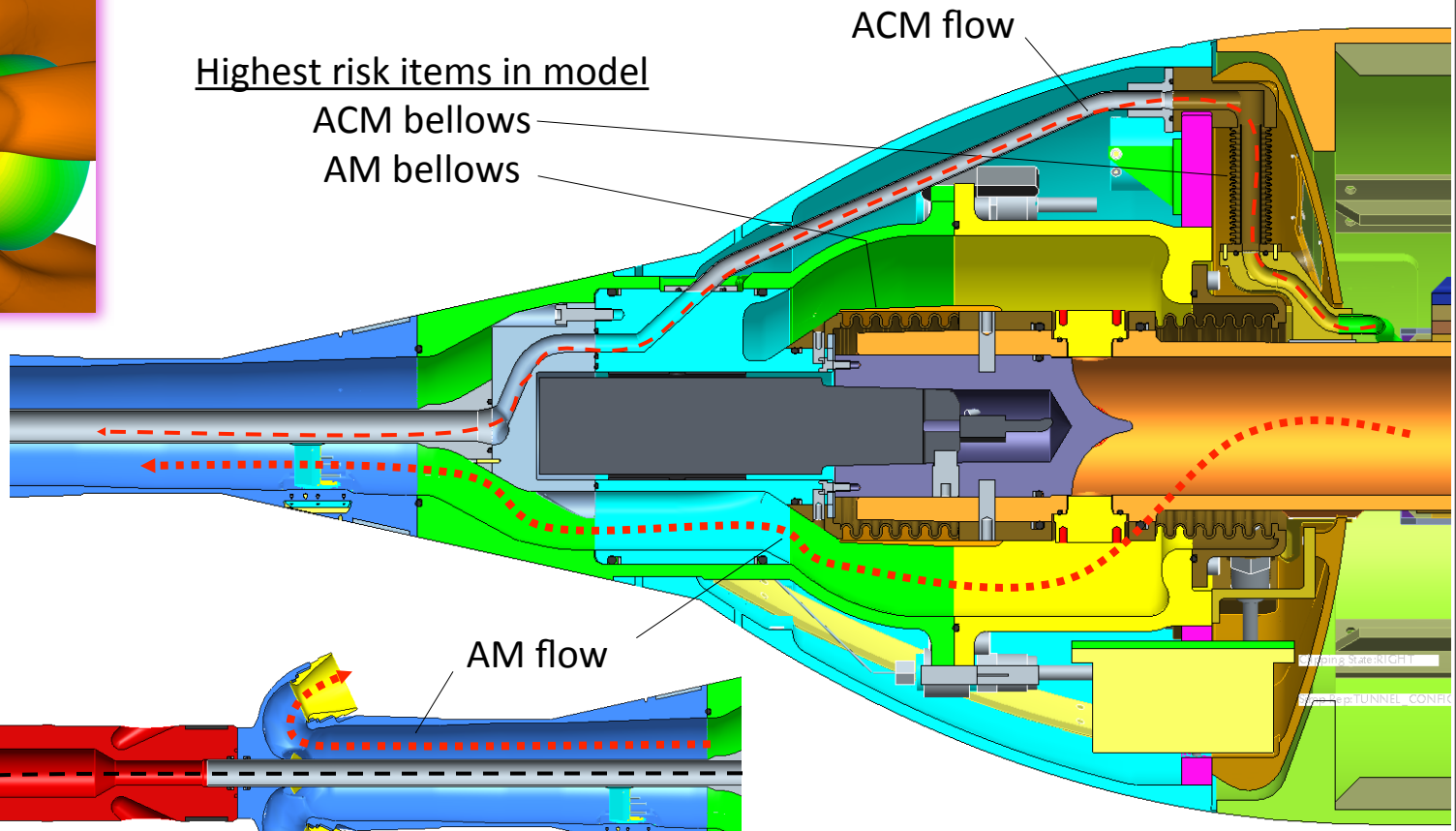
Marvin Sellers

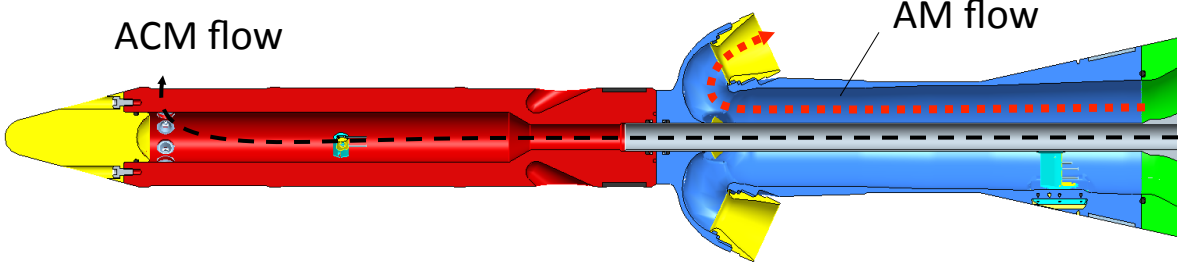
Wim Ruyten

Model Concept for Separation Aero and AM/ACM Plume Jet Interaction Test 26-AA









v0.61 summary

- 26-AA Boost Phase WTT conducted Summer of 2010
  - Obtained Boost ACM aero data, AM JI aero data and separation aero data
  - Data used to update Boost Phase aero environments (F&M and air loads) in the v0.61 database update
- v0.61 database update
  - 26-AA data enabled redefinition of boost ACM environments from low fidelity to mid fidelity
    - ACM control authority is generally less efficient than in v0.60
    - ACM static stability effects are generally more stable than in v0.60
  - 26-AA data enabled redefinition of AM JI environments from low fidelity to mid fidelity
    - AM JI aero is generally more stable than in v0.60
  - 26-AA data enabled redefinition of the uncertainties
    - Total uncertainties are significantly smaller through transonic, supersonic
  - 26-AA data enabled redefinition of the boost phase air loads database from low fidelity to mid fidelity
- Highly successful test program and database development process
  - Most accurate characterization of LAV aerodynamics to date

Plume/Jet Scaling Parameters

TABLE I

Summary of Scaling Parameters

Jet Characteristic	*General Simulation Parameter*	*Simulation Parameter for Matched Stream Conditions and Jet Pressure Ratio*
Boundary in Quiescent Medium	$\left(1 - \frac{p_\infty}{p_j}\right)\frac{\beta_j}{\gamma_j M_j^2}$	$\frac{\gamma_j M_j^2}{\beta_j}$
Boundary in Moving Stream	$\left(\frac{p_j - p_2}{p_2 - p_\infty}\right)\frac{p_\infty \beta_j \gamma_\infty M_\infty^2}{p_j \beta_\infty \gamma_j M_j^2}$	$\frac{\gamma_j M_j^2}{\beta_j}$
Kinetic Energy	$\frac{\gamma_j M_j^2 (RT)_j}{\gamma_\infty M_\infty^2 (RT)_\infty}$	$\gamma_j M_j^2 (RT)_j$
Momentum	$\frac{p_j \gamma_j M_j^2 A_j}{p_\infty \gamma_\infty M_\infty^2 A_\infty}$	$\gamma_j M_j^2 A_j$
Thrust	$\frac{A_j}{A_\infty \gamma_\infty M_\infty^2}\left[\frac{p_j}{p_\infty}(1 + \gamma_j M_j^2) - 1\right]$	$\gamma_j M_j^2 A_j$

Jet Simulation in Ground Test Facilities
M. Pindzola, AGARDograph79, 1963

Most analyses of plume problems assume that, since the momentum within the plume is conserved, a jet can be characterized by its momentum flux at the nozzle exit. Consequently, early Shuttle RCS tests concentrated on ***momentum ratio***, ***jet exit pressure ratio***, and ***scaled nozzle area*** matching (which also matches ***thrust ratio***)…

Plume/Flowfield Jet Interaction Effects on the Space Shuttle Orbiter During Entry, Kanipe, D.B., AIAA-82-1319

CAP project discussed scaling early on, and after consulting with LM and the THAAD and Patriot missile community, decided that matching ***exit Mach number*** and ***thrust ratio***, and ***geometrically scale exit area***, was the proper scaling methodology for aerodynamic interactions.

Summary

- **Culturally, we, as aerodynamicists have to apply our tools appropriately and be better participants in the design process**
  - If you need an aerodynamic database, you need to a good test program and use CFD appropriately
  - If you are doing a scoping study, CFD is appropriate
- **Blunt bodies and plume jet interaction aero is highly dependent on turbulence models, plume scaling and Reynolds numbers**
  - Wake dominated and turbulence dominated flows are still weak areas for CFD and WTT
  - Need to have validation data to determine and validate turbulence models
- **Dynamic damping characterization for blunt bodies at subsonic transonic Mach is best done with large amplitude forced oscillation, but only one facility (TDT) capable of doing this**
- **Uncertainties are a painful process and it would be good to have guidelines for defensible uncertainties**